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2017 Coastal Master Plan

Appendix C: Modeling

Report: Version III

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Prepared By: The Water Institute of the Gulf

Coastal Protection and Restoration Authority

This document was prepared in support of the 2017 Coastal Master Plan being prepared by the Coastal Protection and Restoration Authority (CPRA). CPRA was established by the Louisiana Legislature in response to Hurricanes Katrina and Rita through Act 8 of the First Extraordinary Session of 2005. Act 8 of the First Extraordinary Session of 2005 expanded the membership, duties, and responsibilities of CPRA and charged the new authority to develop and implement a comprehensive coastal protection plan, consisting of a master plan (revised every five years) and annual plans. CPRA's mandate is to develop, implement, and enforce a comprehensive coastal protection and restoration master plan.

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Executive Summary

Coastal Louisiana has experienced dramatic land loss since at least the 1930's. A combination of natural processes and human activities has resulted in the loss of over 1,880 square miles since the 1930's and a current land loss rate of 16.6 square miles per year. Not only has this land loss resulted in increased environmental, economic, and social vulnerability, but these vulnerabilities have been compounded by multiple disasters, including hurricanes, river floods, and the 2010 Deepwater Horizon oil spill, all of which have had a significant impact on the coastal communities in Louisiana and other Gulf coast states. To address this crisis the 2007 Coastal Master Plan was developed under the direction of the Louisiana Legislature. 2012 marked the first five-year update to the plan, and the second update is scheduled for 2017.

A number of substantial revisions have been made in preparation for the 2017 Coastal Master Plan modeling effort. Chapter 1 provides an overview of the modeling improvements and other components of the Master Plan with which the modeling is associated. Brief descriptions of project modeling and the interaction of the modeling with the Planning Tool are included, as is an overview of the external peer review of the 2012 modeling tools and the 2017 model improvement planning process. Lastly, Chapter 1 provides information on the Predictive Models Technical Advisory Committee (PM-TAC), external reviews, and a comprehensive list of 2017 Coastal Master Plan modeling team members.

An overview of improvements made to the modeling tools since 2012, including descriptions of entirely new subroutines and/or processes is provided in Chapter 3. One of the most substantial improvements is the integration of previously disparate models (eco-hydrology, vegetation, wetland morphology, and barrier islands) into an Integrated Compartment Model (ICM). Spatial resolution was increased in the hydrology and morphology subroutines, hydrology compartment configuration was improved, sediment distribution was refined to more accurately capture coastal processes, and marsh edge erosion is now included. The vegetation model has new types of species, including forested wetlands, dune and swale species, and improvements to floating marsh. The vegetation subroutine also improved the dispersal function and establishment and mortality tables, upon which species can become established or lost over time. The barrier island model now includes breaching, overwash/cross-shore profile change, back barrier marsh, wave transformation, and the ability to incorporate explicit storm effects. Hydrology, water quality, and landscape input data sets were updated for use in this modeling effort, and a 50 year record of tropical storms was developed. A number of the habitat suitability indices used in 2012 were revised and others were developed for use in the 2017 modeling effort. Statistical analysis was used to improve HSIs rigor, and they were coded into the ICM. Unlike in 2012, the 2017 Coastal Master Plan modeling effort includes a community fish and shellfish model (Ecopath with Ecosim [EwE]). Lastly improvements were made for storm surge and wave modeling and for risk assessment modeling (CLARA). Improvements include expanded spatial coverage, updated input data, improved internal calculations, and a parametric uncertainty analysis for more insight into the uncertainties associated with the predictions.

Additional details for the modeling components are provided in a series of attachments.

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AA	Atchafalaya-Terrebonne
ADCIRC	Advanced Circulation
AEP	Annual Exceedance Probabilities
ALG	Blue-Green Algae
AVB	Atchafalaya-Vermillion Bay
BIMODE	Barrier Island Model
BLH	Bottom Land Hardwood
BRT	Brenton Sound
C	Habitat Capacity
CAS	Calcasieu
CIMS	Coastal Information Management System
CLARA	Coastal Louisiana Risk Assessment
CLEAR	Coastal Louisiana Ecosystem Assessment And Restoration
CORS	Continuously Operating Reference Stations
CP	Chenier Plain
CPRA	Coastal Protection And Restoration Authority
CPU	Catch Per Unit Effort
CRMS	Coastwide Reference Monitoring System
CV	Coefficient Of Variation
DEM	Digital Elevation Model
DET	Detritus
DON	Dissolved Organic Nitrogen
DOP	Dissolved Organic Phosphorus
EAD	Expected Annual Damage

ECHAM	Max Planck Institute For Meteorology ECHAM5 General Circulation Model
ESLR	Eustatic Sea Level Rise
EwE	Ecopath With Ecosim
F	Fishing Mortality Rates
FEMA	Federal Emergency Management Agency
FWOA	Future Without Action
GCM	General Circulation Model
GENMOM	USGS and Portland State University GENMOM general circulation model
GEDI	NOAA's Geophysical Fluid Dynamics Laboratory Climate Model 2.0
GIS	Geographic Information Systems
HSDRRS	Hurricane and Storm Damage Risk Reduction System
HSI	Habitat Suitability Index
HURDAT	HURricane DATabases
ICM	Integrated Compartment Model
JPM-OS	Joint Probability Method With Optimal Sampling
LACPR	Louisiana Coastal Protection and Restoration
LBA	Lower Barataria
LCWCRTF	Louisiana Coastal Wetlands Conservation and Restoration Task Force
LDEQ	Louisiana Department of Environmental Quality
LO	Less Optimistic
LPO	Lower Pontchartrain
LTB	Lower Terrebonne
LULC	Land Use and Land Cover
MD	Moderate
MPData Server	Master Plan Data Server
MTTG	Morganza To The Gulf

NARR	North American Regional Reanalysis
NCDC	National Climatic Data Center
NOAA	National Oceanic And Atmospheric Administration
NODC	National Oceanographic Data Center
OECLs	Oyster Environmental Capacity Layers
P	Precipitation
PB	Pontchartrain-Barataria
PDI	Power Dissipation Index
PM-TAC	Predictive Models Technical Advisory Committee
PR	Plausible Range
QA/QC	Quality Assurance And Control
RAID	Redundant Array Of Independent Disks
RSLR	Relative Sea Level Rise
RSP	Regularly-Spaced Points
SAL	Salinity
SAV	Submerged Aquatic Vegetation
SBEACH	Storm Induced Beach Change Model
sFTP	Secure File Transfer Server
SSA	Spatial Statistical Approach
SWAN	Simulating Waves Nearshore
TAC	Technical Advisory Committee
TCEQ	Texas Commission On Environmental Quality
TIP	Total Inorganic Phosphorus
TMP	Water Temperature
TN	Total Nitrogen
TSS	Total Suspended Solids

UBA	Upper Barataria
UnSWAN	Unstructured Simulating Waves Nearshore
UPO	Upper Pontchartrain
USACE	U.S. Army Corp Of Engineers
USGS	U.S. Geological Survey
UTB	Upper Terrebonne
WIS	Wave Information Studies
WLV	Water Level Variability
WOD	World Ocean Database

Chapter 1: Introduction

1.0 Louisiana's Coastal Master Plan Overview and Purpose

Coastal Louisiana has experienced dramatic land loss since at least the 1930's (Couvillion et al. 2011). A combination of natural processes and human activities has resulted in the loss of over 1,880 square miles since the 1930's and a current land loss rate of 16.6 square miles per year (Couvillion et al. 2011). Not only has this land loss resulted in increased environmental, economic, and social vulnerability, but these vulnerabilities have been compounded by multiple disasters, including hurricanes, river floods, and the 2010 Deepwater Horizon oil spill, all of which have had a significant impact on the coastal communities in Louisiana and other Gulf coast states. For example, nine of the 10 costliest U.S. hurricanes have impacted a portion of the Gulf coast, and six of these have occurred in the last decade (Blake, Landsea, and Gibney, 2011). Hurricane Katrina resulted in at least $105 billion in direct property damages (Blake, Landsea, and Gibney, 2011).

Decades of planning have focused on addressing either risk reduction or coastal restoration, or only on specific regions of coastal Louisiana (e.g., Coast 2050 [LCWCRTF, 1998]; LACPR [USACE, 2009]; Morganza PAC [USACE, 2013]). It was not until the hurricanes of 2005 that planning efforts began to integrate coastal restoration planning with coastal protection planning. Under the direction of the Louisiana Legislature, the 2007 Coastal Master Plan was developed, and for the first time in Louisiana, emphasis on coordinated storm protection and coastal restoration planning was outlined. The Coastal Protection and Restoration Authority of Louisiana (CPRA), the state entity responsible for the planning, designing and implementation of coastal protection and restoration projects, is tasked by the Louisiana Legislature to update the master plan every 5 years. For the first update in 2012, CPRA focused on expanding the technical analysis to identify specific projects: those that represent sound investments for Louisiana considering resource and funding constraints and uncertain future conditions. The 2012 Coastal Master Plan built on previous efforts by including a detailed assessment of the future without action and an objective evaluation of the performance of hundreds of previously proposed projects, including nonstructural measures, over the next 50 years. The final 2012 Coastal Master Plan included a specific list of recommended restoration and protection projects and modeled predictions of how those projects might perform. This report supports the 2017 Coastal Master Plan, which builds on the work of all previous planning efforts in coastal Louisiana, leverages knowledge developed by generations of scientists and engineers, and utilizes decades of experience building and maintaining coastal restoration and protection projects across the coast.

The 2017 Coastal Master Plan has five objectives:

1. Reduce economic losses from storm surge-based flooding
2. Promote a sustainable coastal ecosystem by harnessing the processes of the natural system
3. Provide habitats suitable to support coast wide commercial and recreational activities
4. Sustain the unique cultural heritage of coastal Louisiana
5. Promote a viable working coast to support important businesses and industries

The master plan focuses the State's efforts and guides the actions needed to sustain the coastal ecosystem, safeguard coastal populations, and protect economic and cultural resources. The master plan also provides the context needed to evaluate other activities in the coastal zone, including: transportation, navigation, and port projects; oil and gas development; ground water management; and land use planning. It is the guiding document of CPRA and the State of Louisiana's efforts to protect and restore the Louisiana coast.

2.0 2012 Coastal Master Plan Modeling

During the development of the 2012 Coastal Master Plan, 397 individual projects were evaluated within a systems context using a suite of predictive models, as depicted in Figure 1. The linked models predicted change in the conditions of the Louisiana coastal system under two different types of future management strategies, a future without the implementation of additional restoration and risk reduction projects (Future Without Action - FWOA) and a future with implementation of additional projects. The concept of linked models in Louisiana coastal planning was not new, as linked models were applied to aid restoration planning for the 2004 Louisiana Coastal Area Study (USACE, 2004) and several linked models were used to inform the 2007 Coastal Master Plan (CPRA, 2007; Appendix G). However, substantially improved or entirely new feedbacks and linkages among models were developed and utilized to support the 2012 Coastal Master Plan process (Peyronnin et al., 2013). Each of the models provide inputs to other models and/or produce outputs that were used to estimate how the landscape might change and/or how projects might perform on the landscape over time.

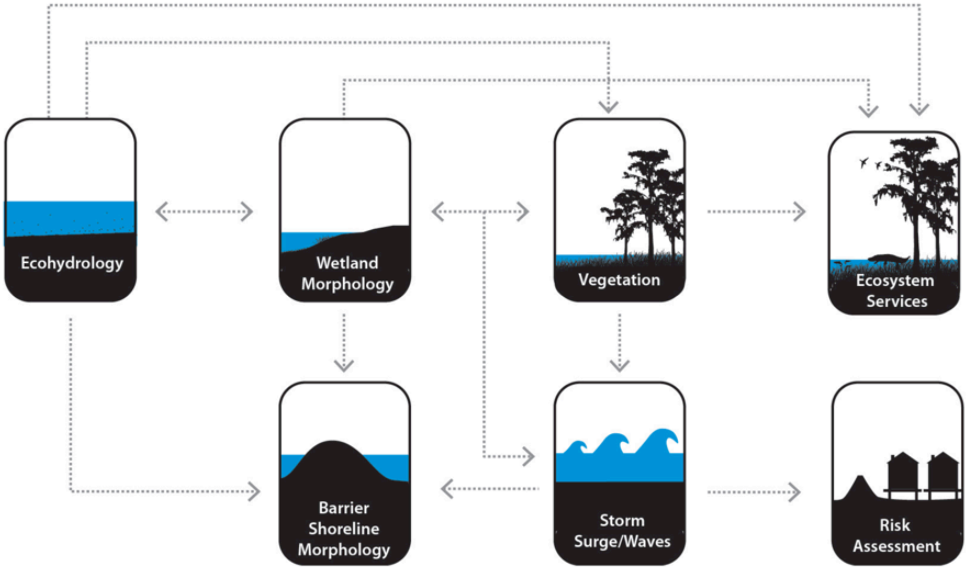

Figure 1: 2012 Coastal Master Plan Predictive Models.

The 2012 Coastal Master Plan modeling components were:

- **Eco-hydrology** - The eco-hydrology model consisted of three individual models (encompassing the Chenier Plain region, the Atchafalaya-Terrebonne region, and the Pontchartrain-Barataria region) that were integrated to provide coast wide outputs (Meselhe et al., 2013). Each model predicted the salinity, stage, and other selected water quality constituents of the open water bodies (including channels) within estuaries using a mass balance approach to estimate the exchanges of solids and chemicals due to advection and dispersion.

- **Wetland morphology** - This model tracked the changes in wetland-dominated landscapes over time including the loss of existing wetlands, the creation of wetlands by both natural and artificial process, and the fate of those newly created wetlands (Couvillion et al., 2013). Whereas previous modeling efforts simply projected past trends into the future, this model considered more characteristics of the landscape as predictors of change.
- **Barrier shoreline morphology** - Changes in barrier shorelines and headlands were derived from a simple shoreline change model driven by analysis of historical shorelines that are a part of the Barrier Island Comprehensive Monitoring project (BICM) (Hughes et al., 2012).
- **Vegetation** - The vegetation model predicted the extent of 19 types/communities of emergent vegetation and submerged aquatic vegetation (Visser et al., 2013). It estimated spatial and temporal changes in vegetation types/communities based on environmental drivers such as salinity and water level change.
- **Ecosystem services** - These models were used to predict how well Louisiana's future coast will provide habitat for commercially and recreationally important coastal species, and key services for coastal communities (Nyman et al., 2013). In total, 19 ecosystem service models were utilized to reflect species habitat, surge/wave attenuation potential (restoration projects only), nature-based tourism, freshwater availability, potential for agriculture/aquaculture, nitrogen uptake potential (Rivera-Monroy et al., 2013), and carbon sequestration potential (CPRA 2012).
- **Storm surge/waves** - For risk reduction projects or groups of projects, this model used the widely-adopted ADCIRC large domain storm surge model coupled with the unstructured SWAN wave model (Cobell et al., 2013). ADCIRC uses an unstructured mesh that allows for variation of resolution from coarse in the open ocean to very fine near islands, channels, levees, and areas where flow gradients are large (such as in channels and wave breaking zones).
- **Risk assessment** - This model estimated residual economic damage from storm surge flooding by predicting the overtopping of flood risk reduction structures due to surge and waves, assessed probabilistically any flooding due to breaching of hurricane risk reduction systems, calculated flood elevations, and identified economic consequences (Johnson, Fischbach, and Ortiz, 2013).

An uncertainty analysis was also conducted for the models addressing change in the coastal landscape and ecosystem (Habib and Reed, 2013). Typically, an uncertainty analysis is implemented such that all sources of parameter uncertainties are propagated starting from the first model (e.g., eco-hydrology), through the intermediate models (e.g., wetland morphology) and ending with the last model(s) (e.g., ecosystem service models). This approach, however, requires an excessively large number of simulations. Instead, the adopted analysis started from the end of the modeling components, focusing on the important outputs, and then worked back to determine the most 'uncertain' parameters that were most relevant for such outputs. This approach was driven by the master plan focus on assessing both near and long-term effects of proposed protection and restoration projects. The analysis found that model predictions of land area 20 years into the future in most regions have uncertainty bounds of less than ±5% if a confidence interval of (25-75%) is used, and less than ±10% if a confidence interval of (10-90%) is used. Furthermore, the uncertainty in land area predictions was similar across the different regions along the coast, and uncertainties of model predictions of land area became larger as the prediction extended into the future years.

3.0 Modeling Improvements

Following the completion of the 2012 Coastal Master Plan, a thorough technical peer review of the models was conducted, and the process generated a number of recommendations for model improvements. The 2012 Habitat Suitability Indices (HSIs) did not undergo review. Recommendations for improvement were also made by the 2012 Coastal Master Plan modeling teams. To consider potential improvements in the models for use in support of the 2017 Coastal Master Plan, local, national, and international experts were engaged during two 'brainstorming workshops' in fall 2012 to discuss and establish the technical aspects for developing a refined modeling approach. In general, recommendations pointed to the development of a more integrated and process-based modeling framework for hydrodynamic, morphological, and ecological components, as well as an increase in the resolution and detail. For models supporting risk assessment, the focus was on improving data sources and consideration of parametric uncertainty.

Based in part on the recommendations of the technical peer review of the 2012 models and input from the modeling teams, a Model Improvement Plan (CPRA, 2013) was developed, which called for a number of desired improvements in the modeling approach including:

- Refining the size of the compartments in the hydrology model to increase the spatial resolution;
- Developing and integrating the simulation of physical and ecological processes controlling landscape and ecosystem dynamics;
- Integrating landscape model components where possible to reduce manual data transfer and facilitate an increase in output frequency; and
- Improving spatial resolution within the risk assessment model, using updated data, and understanding of parametric uncertainty.

Specific recommendations from the external peer review process that were either partially or completely addressed as part of the 2017 modeling update effort are listed below:

Eco-hydrology

- Regional integration
- Better representation of the water, sediment and nutrient budgets
- Improve how sediment flux calculations are implemented in the models
- Synthesize missing data required to drive long-term simulations

Wetland Morphology

- Include mechanistic improvements to soil processes
- Incorporate stochastic effects of storms

Barrier Islands

- Examine and consider developing hybrid models
- Couple island and inlet models more frequently than 25 years
- Incorporate stochastic effects of storms
- Carry out both calibration and validation phases

Vegetation

- Incorporate additional processes into the model (e.g., dispersal/recruitment mechanisms)
- Test/validate the model
- Address model integration and error propagation

Storm Surge

- Improve bottom friction and surface wind stress parameterizations
- Include a larger set of synthetic storms
- Increase commitment of computational resource

4.0 2017 Coastal Master Plan Technical Components

4.1 Modeling

The 2017 modeling effort largely builds on the 2012 Coastal Master Plan models. It was directed by a team made up of CPRA and Water Institute personnel (the Model Decision Team) and carried out largely by a multi-disciplinary team of experts from state and federal agencies, academia, and the private sector; see Table 2 in the 2017 Modeling Team Section. As noted above, the first step was the development of the Model Improvement Plan (CPRA, 2013), which laid out a path forward for the improvements to be made to the modeling tools prior to use for the 2017 Coastal Master Plan. The result was substantial revisions and improvements to the 2012 models, including entirely new modeling approaches in some cases (e.g., barrier islands, fish and shellfish community models). Additional details regarding the modeling are provided in Chapter 3 and in the Attachments to this appendix.

The Integrated Compartment Model (ICM) replaces four previously independent models (eco-hydrology, wetland morphology, barrier shoreline morphology, and vegetation) with a single model code for all regions of the coast (Figure 2). It also includes the components of the previous ecosystem services models that are being carried forward for 2017, and enables integrated execution of the new fish and shellfish community models. Such integration allows for coupling of processes and removes the inefficiency of manual data hand-offs and the potential human error that may occur during the transfer of information from one model to another. The ICM is computationally efficient and can be used for a large number of 50-year, coast wide simulations in a reasonable timeframe. The ICM serves as the central modeling platform for the 2017 Coastal Master Plan to analyze the landscape and ecosystem performance of individual projects and alternatives (groups of projects) under a variety of future environmental scenarios. Key outputs include hydrodynamic variables (e.g., salinity and stage), changes in the landscape (e.g., land-water interface and elevation change, including the barrier islands), and changes in vegetation.

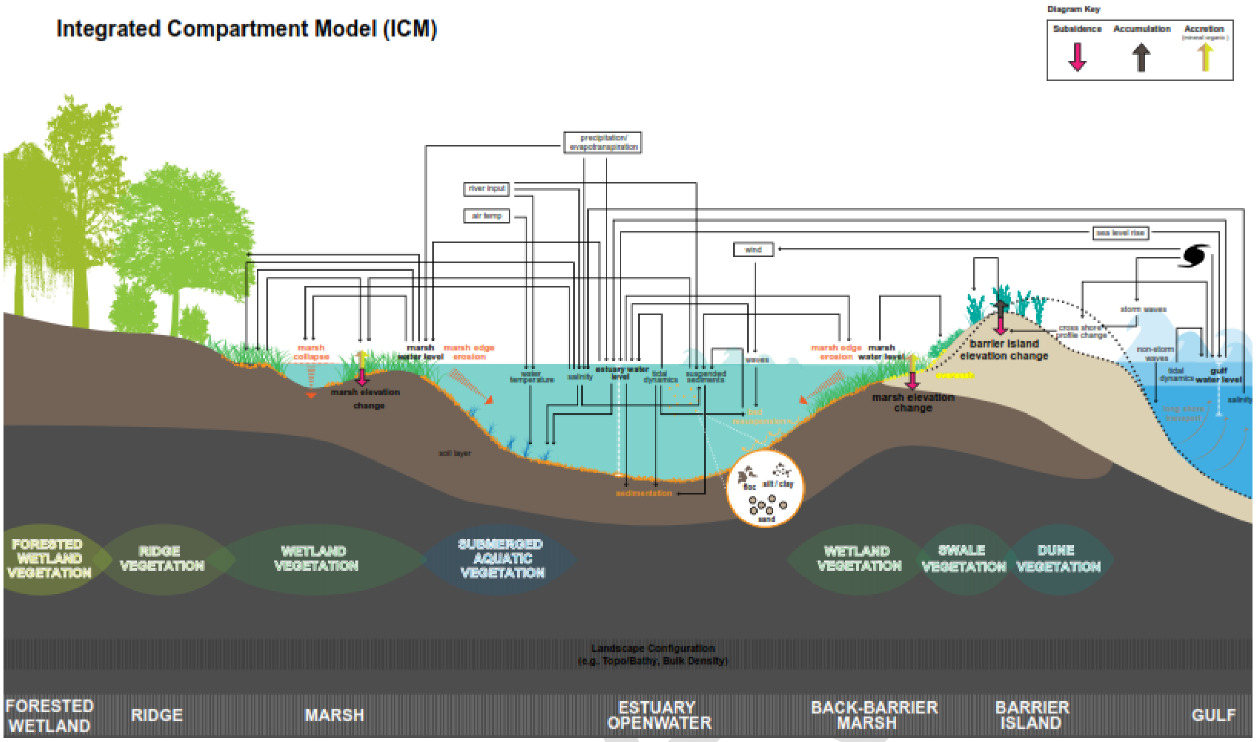

Figure 2: Coastal components and processes represented by the Integrated Compartment Model (ICM).

One new element of the 2017 modeling is the inclusion of fish and shellfish community modeling. A thorough review of fish and shellfish community modeling options was conducted, and ideas were provided on how to select one model over another for use in the 2017 Coastal Master Plan (Rose and Sable, 2013). As a result of this effort, two paths were pursued for improving the representation of fish and shellfish changes in the modeling. A number of improvements were made to the habitat suitability index models (HSIs), including the development of new relationships for many key fish and shellfish based on rigorous statistical analysis and the inclusion of several new indices including blue crab and brown pelican. A total of 19 HSIs are being used for the 2017 Coastal Master Plan and have been integrated into the ICM. In addition, a community modeling approach will be used to evaluate effects of restoration and protection projects on fish and shellfish communities. The model is a spatially explicit ecosystem model (Ecospace model) developed in Ecopath with Ecosim (EwE).

The hydrodynamics, morphology (including barrier islands), and vegetation components of the ICM underwent calibration and validation. Calibration of each component was conducted to the extent possible considering data availability and time in the overall schedule. The EwE model was also calibrated and validated using observed data, and the HSIs underwent 'expert validation' based on best professional judgment of the model's projections of habitat quality. Additional information is provided in Chapter 3 and in the individual Attachments.

Fewer changes were made to the approach used for surge and risk modeling. The ADCIRC-SWAN model is being used for storm surge and waves. The model geometry was updated to improve prediction in some areas, and the revised model was validated with observed data from Gustav and Ike. Approaches to incorporate raised features in the model grid, adjust the wind drag formulation, and assess symmetrical versus asymmetrical storm patterns were also explored. Improvements to the Coastal Louisiana Risk Assessment model (CLARA) include expanding the model domain to account for a growing floodplain, creating a high resolution spatial unit designed to inform local planning in coastal communities, updating and improving the inventory of coastal assets at risk, and developing new scenarios of levee fragility to capture the wide range of uncertainty.

The future environmental scenarios that were used in 2012 (CPRA, 2012) were revised based on updated literature reviews, newly data and technical understanding, as well as sensitivity testing of the ICM to the various parameters (e.g., eustatic sea level rise, subsidence, precipitation). See Chapter 2 Future Scenarios and associated attachments) for additional details regarding the revised scenarios.

4.2 Project Information

The models are used to assess the individual and collective effects of groups of projects on the coastal ecosystem and the level of risk to which coastal communities are exposed. Projects are generally categorized as restoration or protection projects and evaluated according to their restoration or protection effectiveness. However, the effects of individual restoration projects (i.e., a protection effect) on coastal flooding can be generally evaluated using the ICM. When restoration and protection projects are combined in alternatives, both the ICM and the surge/risk models can be used to evaluate the net effect on both the ecosystem and levels of risk. Table 1 below provides a general description of the project types. Additional information regarding project development can be found in Appendix A - Project Definition.

Table 1: Project information for evaluation by the modeling tools.

	Project type	General description
Restoration	Hydrologic restoration	Hydrologic restoration projects aim to maintain coastal wetlands and improve ecosystem outcomes by altering hydrology. They often include combinations of culvert, gates, locks, plug, weirs, etc. Links between compartments in the ICM are adjusted to reflect the changes.
	Shoreline protection	Shoreline protection projects seek to maintain land by reducing the amount of erosion along bay and channel shorelines using structures in the open water adjacent to the shoreline. Within the ICM, the marsh edge erosion rate in the influence area behind the structure is adjusted.
	Bank stabilization	Bank stabilization projects reinforce bank lines by adding material, thus reducing the erosion of the shoreline. Within the ICM, the marsh edge erosion rate in the area influenced by the additional material is adjusted.
	Oyster barrier reef	Oyster barrier reef projects build a submerged structure similar in elevation to a natural oyster reef with the aim of maintaining land by reducing the amount of erosion along adjacent bay and lake shorelines. Within the ICM, the marsh edge erosion rate in the area influenced by the reef is adjusted and the availability of cultch for oyster habitat is increased.
	Ridge restoration	Ridge projects seek to recreate the skeleton of the coastal wetlands along previous distributary channels, providing diverse, higher-elevation habitats and more structure for estuarine hydrology. Within the ICM, the ridge is represented in the topography, and hydrology links are adjusted to account for flow changes.

	Marsh creation	Marsh creation projects use fill material to convert shallow open water areas (<0.76 m deep) into wetlands. Vegetative plantings are usually included. Within the ICM, topography and bathymetry are adjusted, vegetation cover is changed, and hydrology links are adjusted as necessary.
	Diversion	Sediment and freshwater diversion projects seek to convey freshwater and associated sediments from either the Mississippi or Atchafalaya rivers into adjacent wetlands. Within the ICM, freshwater and sediment are released into the compartment(s) adjacent to the diversion location and are distributed throughout the estuarine basins by the hydrology subroutine.
	Barrier island restoration	For barrier island projects, a standard 'restored' template is applied to the area being restored, and cross-shore elevation profiles within the barrier island (BIMODE) subroutine are changed within the footprint of the island restoration. Within BIMODE, the new profiles are then subject to barrier island processes such as cross-shore and long-shore changes and breaching.
Protection	Structural protection	Structural protection projects usually include systems of levees, floodgates, floodwalls, and pumps designed to reduce the flooding of residential, commercial, and industrial assets. Within the ADCIRC/SWAN model, the grid is adjusted to account for the barriers and resulting flood depths are calculated for a set of synthetic storms. CLARA takes this information and develops more detailed flooding maps for the calculation of economic damages to these assets.
	Nonstructural protection	Nonstructural protection projects include structure elevations, floodproofing, or structure acquisitions. CLARA uses flood depths from ADCIRC/SWAN and examines the cost-effectiveness and other parameters of these projects in different communities across the coast.

4.3 Planning Tool

As part of 2012 Coastal Master Plan, CPRA supported the development of a computer-based decision-support tool called the Planning Tool. The Planning Tool was used to: (1) make analytical and objective comparisons of hundreds of different risk reduction and restoration projects, (2) identify and assess groups of projects (called alternatives) that could make up comprehensive solutions, and (3) display the tradeoffs interactively to support iterative deliberation over alternatives (Groves and Sharon, 2013). Similar to the proposed improvements for the models that will support the 2017 Coastal Master Plan, the Planning Tool has also undergone a number of revisions (e.g., improved visualization of outputs, ability to compare 2012 versus 2017 information, adjustments to project selection procedures) described in Appendix D – Planning Tool.

The two fundamental model outputs used by the Planning Tool are the extent of land (output from the ICM) and reduction in expected annual damages (EAD), which is output from the risk reduction model, CLARA. These are termed 'decision drivers.' For each restoration and protection (both structural and nonstructural) project, the cost-effectiveness of the project in terms of each of the decision drivers is used to select the optimal group of projects for a given stream of funding and environmental scenario.

In addition to the decision drivers, a number of additional metrics are derived from the model outputs and used by the Planning Tool to explore the effects of individual projects and groups of projects (alternatives) on other aspects of the coastal system. These include flooding of historic properties, effect on navigation, changes to traditional fishing communities, etc. Many of these metrics combine information derived from CLARA analysis of protection projects and ICM analysis of restoration projects, and thus can only be used to consider the effects of alternatives. Other metrics, such as the effect on navigation or flooding of historic properties use only outputs from CLARA or the ICM and can thus be used as constraints in the formulation of cost-constrained alternatives (e.g., the Planning Tool selects the most cost-effective set of projects that reduces EAD but also ensures only a limited number of historic properties are flooded). Descriptions of these metrics and the inputs they use from the various models are described in Attachment B1 – Metrics Report.

5.0 Model Review

5.1 2012 Coastal Master Plan

Review of model development and application occurred throughout the development of the 2012 Coastal Master Plan. Several Technical Advisory Committees (TACs) were convened including one specifically for the Predictive Models (PM-TAC). Additionally, the Science and Engineering Board reviewed and commented on all aspects of the Master Plan development process, including the modeling.

The PM-TAC focused their review and comment on the effectiveness of the models for predicting project effects. The committee included four well known scientists with expertise and experience not only with issues concerning coastal Louisiana, but also issues of national and international concern. PM-TAC members participated in monthly conference calls and webinars with CPRA leads on the modeling effort, but formal reporting was not part of their role/task. They served in a more informal role of providing technical advice and guidance during the process. To close out the PM-TAC effort, each member was asked to write a brief overview of his or her experience as a PM-TAC member for the 2012 Coastal Master Plan modeling effort (CPRA, 2012b – Appendix H).

Following completion of the 2012 Coastal Master Plan, the model reports included as appendices to the master plan, were subject to an independent technical review (described previously). This review engaged 12 external topical experts and seven expert review editors. Many suggested improvements were undertaken as part of the 2017 Coastal Master Plan Model Improvement Plan.

5.2 2017 Coastal Master Plan Predictive Models Technical Advisory Committee

During the 2012 Coastal Master Plan process, the PM-TAC only met in person once with the modeling team. This limited their ability to interact and discuss problems and solutions directly with those working on model development. The 2012 PM-TAC unanimously recommended that more frequent in-person meetings during future efforts would enhance the overall efficacy of the review process. To convene a TAC for 2017, the Modeling Decision Team identified the five experts listed below (with their professional affiliations) to serve as “over the shoulder” technical advisors throughout the model improvement process. This team of experts comprised the 2017 PM-TAC. They were selected based on their technical area of expertise and their ability to share insight and experience from other relevant efforts.

- **John Callaway (Chair)**, University of San Francisco
- Scott Hagen, University of Central Florida[1]
- Courtney Harris, Virginia Institute of Marine Science
- Wim Kimmerer, San Francisco State University
- Mike Waldon, Retired USFWS

In contrast to traditional peer review, which often only engages toward the end of efforts (e.g., once draft reporting is available,) the PM-TAC has ongoing engagement directly with the modelers, providing working-level assistance throughout the 2017 Coastal Master Plan modeling process. The PM-TAC participates in approximately quarterly in-person meetings in conjunction with the modeling leads for each of the main subroutines or model components. Additional information is provided in Attachment C1-3 (PM-TAC Meeting Reports).

5.3 2017 External Review

An external review of select technical components of the 2017 Model Improvement Plan has also been conducted. The intent was to ensure technical soundness of the modeling strategies and use of equations (particularly associated with the model improvements and newly developed processes) and alert CPRA to any limitations that were not identified by the modeling team. To encourage reviewers to express their views freely, reviewer comments and recommendations remained anonymous when submitted to the model developers. Reviewer comments and recommendations and model developer responses are tracked to provide a record of the process.

In addition to report-specific questions, each reviewer was asked to provide comments in relation to the following review questions:

- Does the documentation clearly / adequately reflect the modeling process?
- Is the overall strategy appropriate for large scale (entire Louisiana coast), long-term (50-year) planning efforts?
- Are the technical assumptions and use of equations acceptable?
- Are there any fundamental flaws or otherwise that should be noted and/or revised for future coastal planning efforts?

The reports that have been subject to review include:

- Sediment Distribution (Attachment C3-1)
- Marsh Edge Erosion (Attachment C3-2)
- Barrier Island Model Development (BIMODE) (Attachment C3-4)
- Vegetation (Attachment C3-5)
- Habitat Suitability Indices (Attachments C3-6 through C3-19)
- EwE (Attachment C3-20)
- CLARA – Risk Assessment (includes discussion of storm surge/waves model analysis and improvements; Attachment C3-25)

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[1] Dr. Hagen transitioned to a new position at Louisiana State University after his engagement as a member of the TAC commenced.

6.0 2017 Modeling Team

As previously mentioned, the 2017 Coastal Master Plan modeling team was directed by a team made up of CPRA and Water Institute personnel (the Model Decision Team) and the technical work was carried out largely by a multi-disciplinary team of experts from state and federal agencies, academia, and the private sector (Table 2).

Table 2: 2017 Coastal Master Plan modeling team members.

Organization	Name
Model Decision Team	
Water Institute	Ehab Meselhe
Water Institute	Denise Reed
Water Institute	Alaina Owens Grace
Coastal Protection & Restoration Authority	Mandy Green
Coastal Protection & Restoration Authority	David Lindquist
Coastal Protection & Restoration Authority	Angelina Freeman
Sediment Distribution	
University of New Orleans	Alex McCorquodale (Subtask Leader)
Moffatt & Nichol	Jeff Shelden
USGS National Wetlands Research Center	Gregg Snedden
USGS National Wetlands Research Center	Hongqing Wang
USGS National Wetlands Research Center	Brady Couvillion
Water Institute	Ehab Meselhe
Water Institute	Ben Roth
Water Institute	Denise Reed
Water Institute	Eric White
Marsh Edge Erosion	
Water Institute	Mead Allison (Subtask Leader)
Water Institute	Brendan Yuill

Organization	Name
Water Institute	Cyndhia Ramatchandirane
Water Institute	Denise Reed
Water Institute	Eric White
Louisiana State University	Q. Jim Chen
University of New Orleans	Alex McCorquodale
USGS National Wetlands Research Center	Brady Couvillion
Barrier Islands	
Coastal Engineering Consultants	Michael Poff (Subtask Leader)
Coastal Planning and Engineering - CBI	Gordon Thomson
Coastal Planning and Engineering - CBI	Morjana Signorin
Coastal Planning and Engineering - CBI	Samantha Danchuk
Coastal Planning and Engineering - CBI	Zhifei Dong
Deltares	Dirk-Jan Walstra
University of New Orleans	Mark Kulp
University of New Orleans	Ioannis Georgiou
Coastal Protection & Restoration Authority	Mark Leadon
Vegetation	
UL Lafayette	Jenneke Visser (Subtask Leader)
UL Lafayette	Scott Dyke-Sylvester
UL Lafayette	Mark Hester
UL Lafayette	Whitney Broussard
UL Lafayette	Jonathan Willis
UL Lafayette	David Horaist
Southeastern LA University	Gary Shaffer
USGS National Wetlands Research Center	Brady Couvillion

Organization	Name
USGS National Wetlands Research Center	Holly Beck
Habitat Suitability Indices	
Moffatt and Nichol	Buddy Clairain (HSI - Subtask Co-Leader)
Moffatt and Nichol	Stokka Brown
UL Lafayette	Paul Leberg
Louisiana State University AgCenter	Robert Romaire
USGS National Wetlands Research Center	Hardin Waddle
Louisiana State University	Jay Geaghan
Water Institute	Ann Hijuelos (HSI - Subtask Co-Leader)
Water Institute	Leland Moss
University of New Orleans	Meg O'Connell
Dynamic Solutions	Shaye Sable
Coastal Protection & Restoration Authority	David Lindquist
Ecopath with Ecosim	
George Mason University	Kim de Mutsert (Subtask Leader)
George Mason University	Kristy Lewis
Louisiana State University	James Cowan
Ecopath Research and Development Consortium	Jeroen Steenbeek
Ecopath Research and Development Consortium	Joe Buszowski
University of Southern Mississippi	Scott Milroy
Metrics	
Water Institute	Scott Hemmerling
Water Institute	Melissa Baustian
Water Institute	Denise Reed

Organization	Name
Water Institute	Ann Hijuelos
Coastal Protection & Restoration Authority	Melanie Saucier
Input Datasets and Boundary Conditions	
Moffatt and Nichol	Stokka Brown (Subtask Co-leader)
USGS National Wetlands Research Center	Brady Couvillion (Subtask Co-leader)
USGS National Wetlands Research Center	Holly Beck
Develop Future Scenarios	
Water Institute	Ehab Meselhe (Subtask Leader)
Fenstermaker	Jenni Schindler
Fenstermaker	Mallory Rodrigue
Moffatt and Nichol	Zhanxian ‘Jonathan’ Wang
Moffatt and Nichol	Stokka Brown
USGS National Wetlands Research Center	Brady Couvillion
UL Lafayette	Jenneke Visser
UL Lafayette	Scott Duke-Sylvester
UL Lafayette	Emad Habib
Coastal Protection & Restoration Authority	Jim Pahl
Water Institute	Denise Reed
Water Institute	Eric White
Integrated Compartment Model Development	
Water Institute	Ehab Meselhe (Subtask Leader)
Water Institute	Eric White
University of New Orleans	Alex McCorquodale
Moffatt and Nichol	Zhanxian ‘Jonathan’ Wang
Moffatt and Nichol	Stokka Brown

Organization	Name
Fenstermaker	Mallory Rodrigue
Fenstermaker	Jenni Schindler
USGS National Wetlands Research Center	Brady Couvillion
USGS National Wetlands Research Center	Bill Sleavin
UL Lafayette	Jenneke Visser
UL Lafayette	Scott Duke-Sylvester
Coastal Planning and Engineering - CBI	Gordon Thomson
Coastal Planning and Engineering - CBI	Samantha Danchuk
Coastal Planning and Engineering - CBI	Morjana Signorin
Coastal Planning and Engineering - CBI	Zhifei Dong
Storm Surge and Risk Assessment Model Improvements	
Arcadis	Hugh Roberts (Subtask Leader)
Arcadis	John Atkinson
Arcadis	Zach Cobell
Arcadis	Haihong Zhao
RAND	Jordan Fischbach (Subtask Leader)
RAND	David Johnson
RAND	Ricardo Sanchez
RAND	Chuck Stelzner
RAND	Rachel Costello
RAND	Kenneth Kuhn
ICM Calibration & Uncertainty Analysis	
Water Institute	Ehab Meselhe (Subtask Leader)
Water Institute	Eric White
Water Institute	Yushi Wang

Organization	Name
Water Institute	Denise Reed
University of New Orleans	Alex McCorquodale
Moffatt & Nichol	Stokka Brown
Moffatt & Nichol	Zhanxian ‘Jonathan’ Wang
Moffatt & Nichol	Mark Dortch
Fenstermaker	Mallory Rodrigue
Fenstermaker	Jenni Schindler
USGS National Wetlands Research Center	Brady Couvillion
UL Lafayette	Emad Habib
UL Lafayette	Jenneke Visser
UL Lafayette	Scott Duke-Sylvester
Coastal Planning and Engineering - CBI	Gordon Thomson
Coastal Planning and Engineering - CBI	Morjana Signorin
Coastal Planning and Engineering - CBI	Zhifei Dong
Data Management	
Coastal Protection & Restoration Authority	Ed Haywood
USGS National Wetlands Research Center	Craig Conzelmann
USGS National Wetlands Research Center	Kevin Suir

7.0 Structure of Appendix C

This appendix describes the modeling used to support the development of the 2017 Coastal Master Plan. This chapter provides a broad overview of what was done for the 2012 Coastal Master Plan modeling effort, updates that were made, and linkages between the modeling, projects, and the Planning Tool. The procedure for selection of the values included in the environmental scenarios is described in Chapter 2, and Chapter 3 includes a short description of each of the primary modeling components, including boundary condition data. The focus of Chapter 3 is on changes made since the 2012 Coastal Master Plan. More detailed descriptions for each of the main model components, subroutines, and supporting tasks are included in a series of Attachments. Chapters 4 and 5 provide overviews of model output and conclusions, respectively. Chapters that are forthcoming are indicated as such in the list below. Attachments will be posted to the CPRA website as they become available.

Below is a list of attachments associated with Appendix C:

- CHAPTER 1 – Introduction
- CHAPTER 2 – Future Scenarios
    - Attachment C2-1 – Eustatic Sea Level Rise
    - Attachment C2-2 – Subsidence
    - Attachment C2-3 – Precipitation and Evapotranspiration
    - Attachment C2-4 – Tropical Storm Intensity and Frequency
- CHAPTER 3 – Modeling Components & Overview
    - Attachment C3-1 – Sediment Distribution
    - Attachment C3-2 – Marsh Edge Erosion
    - Attachment C3-3 – Storms in the ICM Boundary Conditions
    - Attachment C3-4 – Barrier Island Model Development (BIMODE)
    - Attachment C3-5 – Vegetation
    - Attachment C3-6 – Gadwall Habitat Suitability Index Model
    - Attachment C3-7 – Green-winged Teal Habitat Suitability Index Model
    - Attachment C3-8 – Mottled Duck Habitat Suitability Index Model
    - Attachment C3-9 – Brown Pelican Habitat Suitability Index Model
    - Attachment C3-10 – Alligator Habitat Suitability Index Model
    - Attachment C3-11 – Blue Crab Habitat Suitability Index Model
    - Attachment C3-12 – Oyster Habitat Suitability Index Model
    - Attachment C3-13 – Brown Shrimp Habitat Suitability Index Model
    - Attachment C3-14 – White Shrimp Habitat Suitability Index Model
    - Attachment C3-15 – Gulf Menhaden Habitat Suitability Index Model
    - Attachment C3-16 – Spotted Seatrout Habitat Suitability Index Model
    - Attachment C3-17 – Bay Anchovy Habitat Suitability Index Model
    - Attachment C3-18 – Largemouth Bass Habitat Suitability Index Model
    - Attachment C3-19 – Crayfish Habitat Suitability Index Model
    - Attachment C3-20 – Ecopath with Ecosim (EwE)
    - Attachment C3-21 – Nitrogen Uptake
    - Attachment C3-22 – ICM Integration
    - Attachment C3-23 – ICM Calibration and Validation
    - Attachment C3-24 – ICM Uncertainty Analysis
    - Attachment C3-25 – Storm Surge and Risk Assessment

    - Attachment C3-25.1 – Storm Surge
  - Attachment C3-26 – Hydrology and Water Quality Boundary Conditions
    - Attachment C3-26.1 – Monitoring Station List
    - Attachment C3-26.2 – Flow Data
    - Attachment C3-26.3 – Water Level Data
    - Attachment C3-26.4 – Water Quality Stations and Locations
  - Attachment C3-27 – Landscape Data
  - Attachment C3-28 – Data Management
- CHAPTER 4 – Master Plan Model Results – forthcoming
- CHAPTER 5 – Use of Model Outputs and Conclusions – forthcoming

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Chapter 2: Future Scenarios

9.0 Introduction

9.1 The Need for Scenarios

The objective of Louisiana's Comprehensive Master Plan for a Sustainable Coast is to evaluate and select restoration and protection projects that build and sustain the landscape and reduce risk to communities from storm surge based flooding. Given the uncertainty associated with future environmental conditions, models that seek to predict future outcomes must incorporate some level of variability in their inputs to reflect such uncertainty. This is especially important to help in decision making when planning long-term (50-year), large-scale (coast wide) restoration and protection efforts for coastal Louisiana. There are many ways to consider unknown future conditions, and selecting a strategy to incorporate those conditions into a modeling effort depends on the types of information available and how the results will be used. Where there is no known likelihood associated with environmental conditions but rather a range of plausible future conditions, scenario analysis (e.g., Groves and Lempert, 2007; Mahmoud et al., 2009) provides a viable way for decision makers to explore the effects of different possible future conditions on the outcomes of interest. The primary role of scenarios in the master plan modeling is to provide insight into project performance into the future, across a range of plausible future conditions.

A scenario approach, evaluating model outcomes across different combinations of values for a set of environmental drivers, was used in the development of the 2012 Coastal Master Plan. This effort builds on the work conducted for the 2012 Coastal Master Plan and provides a foundation for the selection of scenario values for the 2017 Coastal Master Plan. The resulting representations of future environmental conditions captured in the scenarios are not intended to represent "what will happen into the future;" instead, they are a means of gaining insight into the uncertainty of the future and an acknowledgement that the past environmental conditions will not necessarily repeat into the future. Including future scenarios in master plan analyses allows for the consideration of a variety of plausible future conditions.

In preparation for the 2012 Coastal Master Plan, nine key environmental drivers were identified for which it was challenging to determine a more or less likely set of values to drive the modeling effort. Some of these environmental drivers are influenced by climate change or management decisions in the future (e.g., eustatic sea level rise [ESLR] and river nutrient concentrations, respectively), and some are based on processes that are not fully understood (e.g., subsidence, marsh collapse threshold). Such complexity made it challenging to identify values for the future scenarios to drive the models.

This report documents the procedures used to explore new data and literature regarding some of the environmental drivers and develop a set of analyses to explore model output response to different values for environmental drivers. These analyses are used to inform the selection of environmental drivers and values to be used in scenarios for the 2017 Coastal Master Plan modeling effort. Such analyses were not conducted prior to the selection of scenario values for use in the 2012 Coastal Master Plan. Consequently, while the values were thought to each contribute to change in model outputs, this hypothesis was not formally tested.

It is important to note that this report does not attempt to develop new science related to the environmental drivers or their temporal/spatial patterns. There is also no attempt to develop new forecasts or predictions of future conditions. Rather, this effort focuses on identifying the state of the science and applying that knowledge for coastal planning purposes. As such, the work is based on a combination of scientific literature, analysis of existing data, input from subject matter experts, and best professional judgment where necessary.

9.2 Developing Scenarios

Scenarios for use in planning can be derived in a number of ways. In some cases, they are developed by stakeholders and in others by using statistical methods to explore the possible range of future circumstances once plausible ranges for individual drivers have been identified. This report outlines options that were considered to explore model output response to changes in environmental drivers and procedure used. All approaches had to be feasible given the time and resource constraints of the planning process.

Once the nine key environmental drivers were identified for the 2012 Coastal Master Plan analysis, documentation was assembled to describe the plausible range of each driver over the 50-year planning horizon (Table 3). In some cases, this documentation was based on a review of the scientific literature. In other cases, ranges were generated using expert panels and/or inspection of available historical data. Once a plausible range for each driver is established, there are a number of ways scenario values can be selected. For 2012, expert opinion was used to select values from within each of the ranges. These selected values were then combined into a small set of future scenarios. One disadvantage of this approach is that while relatively simple to explain to stakeholders (especially compared to some of the statistical approaches used by others), the role of any individual driver in influencing model outcomes cannot be determined. Stakeholders may assume all the drivers are equally important; this may or may not be the case. Model outputs may be more sensitive to some environmental drivers than others. If that is the case, scenario analyses could be focused on fewer drivers to enable decision makers to better understand how future conditions influence master plan outcomes. A smaller number of drivers in each scenario also reduces the complexity of communication with stakeholders.

The approaches described in this report involve testing the effects of different values selected from the plausible ranges of several environmental drivers on key model outputs. The results of the model runs can then be explored to show which values across the plausible range of the environmental drivers produce change in model outputs. This information can then be used to inform the selection of a small set of scenario values for use in the 2017 Coastal Master Plan and makes it more likely that the different scenarios will produce a change in master plan model outputs. Not only do the experimental analyses described below facilitate the development of the future scenarios, they also provide valuable insight into overall model sensitivity which can be highly important when interpreting model outputs.

Due to limited time and resources, the experimental analyses described herein to identify scenario values were not applied to the surge and wave modeling component (incorporated using ADCIRC (Advanced CIRCulation Model)), but the surge and wave analyses are responsive to the values chosen for environmental drivers. Future storm surge and wave conditions will be predicted based on landscape conditions where landscape change will be driven by different values of environmental driver associated with each scenario. Some testing of candidate scenario values for storm intensity and frequency in the CLARA model was conducted prior to finalizing the values for the environmental scenarios. Further discussion of scenario values to be used in the risk analysis (e.g., fragility, population growth) can be found in Attachment C3-25.

There are four primary steps in developing scenarios for use in the 2017 Coastal Master Plan:

1. Revisit the 2012 Coastal Master Plan work on future scenarios, select drivers that are relevant to the 2017 analyses, and identify whether plausible ranges for the relevant environmental drivers should be modified, using recent literature, data, and other information;
2. Assess the response of key model outputs to changes in value of the environmental drivers
    a. Design focused numerical experiments and perform analysis to assess the response of key outputs of the 2017 Coastal Master Plan Integrated Compartment Model (ICM)
    b. Sensitivity testing, using 2012 data, with CLARA to ensure that variation in storm frequency and intensity would influence the performance of risk reduction projects;
3. Conduct ICM model runs on a range of candidate scenario values to confirm outputs based on combinations of driver values; and
4. Identify three scenarios (combination of values of environmental drivers) to be used in the 2017 Coastal Master Plan modeling effort.

Because scientific understanding of environmental conditions continues to grow and evolve, fall 2014 (time this report was written) was used as the ‘stopping point’ for new information to be included/considered in the identification of plausible ranges, as time is needed for the technical team to implement the experimental model runs and design the scenarios that will be used in the 2017 Coastal Master Plan modeling. New information and data made available after fall 2014 will be included in future master plan updates.

10.0 Selection of Drivers and Identification of Ranges

10.1 Revisiting the 2012 Coastal Master Plan

Nine key environmental drivers considered to have uncertain outcomes over the next 50 years were used to develop future scenarios for the 2012 Coastal Master Plan technical analysis. Appendix C – Environmental Scenarios (CPRA, 2012) provides an overview of each of the environmental drivers included, plausible ranges for those drivers across a 50-year planning horizon, and a rationale for selecting values from within those ranges to formulate the future scenarios. Table 3 provides an overview of the drivers, plausible ranges considered, and the values used to define two future scenarios – ‘moderate’ and ‘less optimistic’ – for the 2012 Coastal Master Plan. A third scenario was also incorporated in the final 2012 analysis; this scenario was identical to the ‘moderate’ scenario but had a eustatic sea level rise (ESLR) value of 0.78 m over 50 years.

Table 3: Overview of the environmental uncertainties ('drivers' in 2017 analyses) and values used to define two future scenarios for the 2012 Coastal Master Plan.

Environmental Uncertainty	Plausible Range	Moderate Future Value	Less Optimistic Future Value
Eustatic Sea Level Rise	0.16 to 0.65 m over 50 years *(a higher value of 0.78 m over 50 yrs was eventually considered for 'alternative' modeling)*	0.27 m / 50 yr	0.45 m / 50 yr
Subsidence	0 to 35 mm/yr; varies spatially	0 to 19 mm / yr (values vary spatially)	0 to 25 mm / yr (values vary spatially)
Tropical Storm Intensity	Current intensities to +30% of current intensities	+10% of current intensities	+20% of current intensities
Tropical Storm Frequency	-20% to +10% of current frequency	Current frequency; (one Category 3 or greater storm every 19 yr)	+2.5% of current frequency; (one Category 3 or greater storm every 18 yr)
Mississippi River Discharge	-7% to +14% of annual mean discharge; adjusted for seasonality	Mean annual discharge (534,000 cfs)	-5% of mean annual discharge (509,000 cfs)
Rainfall	Historical monthly accumulations (+/- 1 SD); varies spatially (8 points from gridded data field)	Historical monthly averages	25th percentile of historical monthly averages
Evapotranspiration	Historical monthly averages (+/-1 SD); varies spatially (10 interpolated points from North American Regional Reanalysis dataset)	Historical monthly averages	+0.4 SD from historical monthly averages
Mississippi River Nutrient Concentration	- 45% to +20% of current nitrogen & phosphorus concentrations	-12% of current concentrations (mg/L) Phosphorus = 0.19 Nitrite + Nitrate = 1.1 Ammonium = 0.038 Org. Nitrogen = 0.67	Current concentrations (mg/L) Phosphorus = 0.22 Nitrite + Nitrate = 1.3 Ammonium = 0.044 Org. Nitrogen = 0.77
Marsh Collapse Threshold	Salinity (ppt) Swamp: 4-7 Fresh Marsh: 6-8 Inundation (water depth, cm) Intermediate Marsh: 31-38 Brackish Marsh: 20-26 Saline Marsh: 16-23	Mid-range values of salinity and/or inundation result in collapse Salinity (ppt) Swamp: 6 Fresh Marsh: 7 Inundation (water depth, cm) Intermediate Marsh: 34 Brackish Marsh: 23 Saline Marsh: 21	Lower 25th percentile values of salinity and/or inundation ranges result in collapse Salinity (ppt) Swamp: 5 Fresh Marsh: 7 Inundation (water depth, cm) Intermediate Marsh: 33 Brackish Marsh: 21 Saline Marsh: 18

10.2 Why Fewer Drivers are considered for 2017

Early in the model improvement work for the 2017 Coastal Master Plan, model team leaders were asked to identify the most important drivers that should be considered in the scenario analysis. Their recommendation was to begin with the same drivers used in 2012 with the exception of the marsh collapse threshold; it is proposed to explore the influence of uncertainty in this environmental driver during the planned model uncertainty analysis. This is recommended because marsh collapse threshold is not an uncertainty in terms of unknown future environmental conditions; rather, it is an uncertainty of our understanding of the current conditions and processes at work.

A literature and data review was conducted to update the plausible range of each remaining driver by incorporating the latest available information. The list of drivers was later reconsidered, as the ICM began to take shape, in terms of each driver's likely impact on model outcomes. Removing non-critical drivers from the scenario analysis results in a more robust experimental design for testing model response to the remaining environmental drivers – those drivers likely to have a more substantial impact on model outputs. It also reduced the time and resources needed to complete the analysis.

The following is an explanation of the changes made to the list of drivers for 2017 compared to 2012; changes to the ranges are provided in Table 4:

- Mississippi River Discharge – this is being **removed** from the 2017 future scenarios analysis. Based on the literature review conducted, including a review of the literature that was used to identify the range used in the 2012 effort, the recommendation is to remove Mississippi River discharge from the scenario analysis, as there is little evidence to support a change in discharge in the future, and instead use the historical hydrograph without adjustments.

- Precipitation – this is a **change in terminology** from Rainfall in the 2012 effort to indicate inclusion of all forms of precipitation.

- Mississippi River Nutrient Concentration – this is being **removed** from the 2017 future scenarios analysis. The 2017 Coastal Master Plan will model nutrients in the water quality subroutine and with a nitrogen uptake subroutine; however, model outputs that depend on these water quality calculations are not expected to be primary decision drivers in planning efforts. Therefore, future uncertainty of nutrient concentrations is unlikely to alter planning decisions made for the 2017 Coastal Master Plan; this driver will no longer vary across future scenarios.

10.3 Summary of Ranges for 2017 Drivers

This section provides an overview of each environmental driver that is included in the 2017 Coastal Master Plan future scenarios analysis. Overviews include a brief statement regarding the values used in the 2012 Coastal Master Plan and the rationale for setting the plausible 50-year ranges (2015 – 2065) for use in the 2017 Coastal Master Plan. Table 4 compares the 2017 ranges to those used in 2012, including the values used in the 2012 moderate and less optimistic scenarios. Additional details on each of the drivers are provided in Attachments C2-1-C2-4.

Eustatic Sea Level Rise (ESLR)

The 2012 plausible range for ESLR was established on the basis of a data and literature review. The low end of the range assumed no acceleration of the current rate beyond a recent observed linear rate, and the high end of the range assumed acceleration consistent with the National Research Council (NRC, 1987) scenario used to define the high sea level rise scenario for the U.S. Army Corps of Engineers Circular #1165-2-211 (USACE, 2009). For the final 2012 analysis, a 'very high' ESLR rate was incorporated, based on Vermeer and Rahmstorf (2009).

Although the full breadth of historical work on this topic was considered for updating the 2017 range, emphasis was placed on new observations and predictive modeling generated between the 2010 completion of the review that informed the 2012 Coastal Master Plan models and fall 2014. Specifically, input for setting the new range included altimetry data, western Florida tide gauge stations, an updated U.S. Army Corps of Engineers Circular #1165-2-212 (USACE, 2011), National Research Council 2012 sea level rise estimates and regional modifications (NRC, 2012), as well as a set of sea level rise scenarios and regional modifications included in the 2013 5th Assessment Report of the Intergovernmental Panel on Climate Change. To establish the full plausible range of future sea level rise, this review equally evaluated results from both process-based and semi-empirical predictive models. The result is a slightly wider plausible range of values compared to 2012.

Note: only eustatic (global) or regional sea level rise rates were used, as the subsidence component of locally specific relative sea level rise is accounted for separately in the 2017 modeling effort.

For more information on eustatic sea level rise, see Attachment C2-1.

Subsidence

Subsidence, as applied in the 2012 Coastal Master Plan scenarios was derived from a map of plausible subsidence rates (ranging from 0 to 35 mm yr^{-1}) across coastal Louisiana that were differentiated into 17 geographical regions. Recent technical literature, information, and data were identified and reviewed to determine if the accuracy and spatial variability of the 2012 subsidence rates or spatial coverage could be improved. No new definitive studies on subsidence were found to provide coast wide predictions of future rates, and there are issues of concern with the two new data sources considered. For example, the tide gauge data analysis likely better reflects relative sea level rise not enabling the specific identification of subsidence, and the Continuously Operating Reference Stations (CORS) data are largely derived from instrumentation mounted on buildings which may not reflect the open estuary rates.

Considering the lack of definitive data or new studies on which to justify modifying the spatial polygon boundaries, the recommendation is for the 2017 Coastal Master Plan to use the same geographic regions and subsidence rates therein as the 2012 Coastal Master Plan.

For more information on subsidence, see Attachment C2-2.

Precipitation

In the 2012 Coastal Master Plan modeling effort, the plausible range of precipitation (referred to in 2012 as Rainfall) was based on historical monthly accumulations (+/- 1 SD) using records from

1990-2010. Eight precipitation gauges were used to provide the spatial variability of the rainfall pattern across the Louisiana coast.

However, general circulation models (GCMs) are now available and provide information on the impact of greenhouse gas emissions on future climate and are increasingly used to develop regional models of future climate. The availability of both these GCM and regional climate datasets have resulted in the recent incorporation of climate projections in numerous large-scale water resource planning efforts (Hagemann et al., 2012; Huntington et al., 2014; Sankovich et al., 2013).

Three regional climate projections (developed from GFDL, ECHAM, and GENMOM GCM climate projections and dynamically downscaled via the RegCM3 regional climate model; Hostetler et al., 2011) were used to determine a range of future precipitation conditions across coastal Louisiana for use in the 2017 Coastal Master Plan. In addition to these three future projections of climate, historic records of precipitation were considered when developing the plausible range. The low end of the 2017 precipitation range is set by GENMOM data and represents an approximate 5% decrease in 50-year cumulative precipitation compared to historical data. The high end of the range is set by the ECHAM data and represents an approximate 14% increase in 50-year cumulative precipitation compared to historical data.

For more information on precipitation, see Attachment C2-3.

Evapotranspiration

In the 2012 Coastal Master Plan modeling effort, the plausible range of evapotranspiration was based on historical (calculated via Penman-Monteith) monthly accumulations (+/- 1 SD). These monthly values did not vary temporally (e.g., all 50 January evapotranspiration values were the same for each simulated year); however, the data varied spatially across the coast per 10 points extracted from existing datasets derived from climatic data.

The same three regional climate projections used to develop precipitation scenarios (as discussed in the previous section of this report) were also used to determine a range of future evapotranspiration conditions across coastal Louisiana. In addition to these future projections of climate, the historic monthly mean potential evapotranspiration rates (calculated via Penman-Monteith) were considered in developing the plausible range. The low end of the 2017 evapotranspiration range is set by GENMOM data and represents a 30% decrease in 50-year cumulative evapotranspiration compared to historical (Penman-Monteith). The high end of the ranges is set by the Penman-Monteith data and represents historic monthly mean potential evapotranspiration.

For more information on precipitation, see Attachment C2-3.

Tropical Storm Intensity

In 2012, the plausible range tropical storm intensity was based on a suite of literature, including global and regional models and expert input from the 2012 Coastal Master Plan risk assessment modeling team.

Future hurricane intensity was revisited for the 2017 effort and the revised plausible range of future change builds off an updated literature review with expert input from the risk assessment modeling team. The range was drawn from several robust modeling efforts that projected potential changes in tropical storm intensity using central pressure deficit, wind speed, and power dissipation index (PDI). Recommended plausible ranges are based on projections of

Atlantic Ocean Basin changes only, although studies analyzing potential changes in the Pacific and global basins have been noted. Both the literature reviewed and the historical record (since 1980) provide evidence to suggest an increasing trend in tropical storm intensity; therefore an increase in overall intensity compared to existing conditions is suggested for the 50-year period of analysis.

Note: due to the nature of the storms in the synthetic storm suite being used for the 2017 Coastal Master Plan modeling effort, there are limitations in the possible adjustments of storm intensity for the landscape analyses. Therefore tropical storm intensity will not be included in the ICM future scenarios; rather, it will be reserved for use in the risk assessment modeling (ADCIRC and CLARA).

For more information on tropical storm intensity, see Attachment C2-4.

Tropical Storm Frequency

In 2012, the plausible range of tropical storm frequency was based on a suite of literature, including global and regional models and expert input from the 2012 Coastal Master Plan risk assessment modeling team. During this effort, only the frequency of Category 3 hurricanes or higher was considered.

Based on a literature review including projections of recent modeling efforts and expert input from the risk assessment modeling team, several adjustments are suggested. The 2017 Coastal Master Plan will consider all tropical storms and major hurricanes separately, with a decrease in the frequency of all tropical storms and an increase in major hurricanes. Specifically, the 2017 revision proposes a slight reduction in the frequency of all tropical storms compared to what was used in the 2012 Coastal Master Plan but a higher frequency of major hurricanes. Recommended plausible ranges are based on projections of Atlantic Ocean Basin changes only, although studies analyzing potential changes in the Pacific and global basins have been noted.

For more information on tropical storm frequency, see Attachment C2-4.

10.4 Comparison of 2012 and 2017 Values

For ease of comparison, Table 4 provides a summary of the 2012 Coastal Master Plan plausible range and moderate and less optimistic scenario values as well as the plausible range proposed for the 2017 effort.

Table 4: 2017 Coastal Master Plan environmental driver ranges, compared to those used in 2012.

Environmental Driver	**2012 Coastal Master Plan** **Plausible Range (PR)** **Moderate (Md) future scenario** **Less Optimistic (LO) future scenario**	**2017 Coastal Master Plan** **Plausible Range**
Eustatic Sea Level Rise	PR: 0.16 to 0.65 m over 50 years Md: 0.27 m / 50 yr LO: 0.45 m / 50 yr High SLR: 0.78 m / 50 yr	0.14 to 0.83 m over 50 years

Environmental Driver	**2012 Coastal Master Plan** **Plausible Range (PR)** **Moderate (Md) future scenario** **Less Optimistic (LO) future scenario**	**2017 Coastal Master Plan** **Plausible Range**
Subsidence	PR: 0 to 35 mm/yr; varies spatially (See Page 2) Md: 20% into the range (0 to 19 mm / yr) LO: 50% into the range (0 to 25 mm / yr)	Same as 2012
Tropical Storm Intensity	PR: Current intensities to +30% of current intensities Md: +10% of current intensities LO: +20% of current intensities	+4 to +23% of current central pressure deficit
Tropical Storm Frequency	PR: -20% to +10% of current frequency Md: Current frequency; (one Category 3 or greater storm every 19 yr) LO: +2.5% of current frequency; (one Category 3 or greater storm every 18 yr)	All tropical storms: -28% to 0% change of current frequency Major storms: +13% to +83% change of current frequency
Precipitation	PR: Historical monthly accumulations (+/- 1 SD), 1961-1990; varies spatially (8 points taken from gridded data field) Md: Historical monthly average LO: 25th percentile of historical monthly	Low: -5% of 50-yr observed cumulative High: +14% of 50-yr observed cumulative
Evapotranspiration	PR: Historical monthly average (+/-1 SD); varies spatially (10 points taken from existing data) Md: Historical monthly average LO: +0.4 SD from historical monthly average	Low: -30% of 50-yr cumulative Penman-Monteith evapotranspiration High: Historic Penman-Monteith evapotranspiration record

11.0 Analysis to Support Selection of Scenario Values

This section describes the analysis options considered to select the scenario values and the results of the analysis that was used in the selection of the values. The final scenario values for the 2017 Coastal Master Plan and the process used to arrive at these decisions is also presented.

11.1 Suggested Approaches for Value Selection

There are a number of approaches that can be used to select the values used in scenarios. This section outlines two options considered to assess the effects of changing environmental driver values on model output and a description of the 'hybrid' analytical approach used to select the values for scenarios for the 2017 Coastal Master Plan. Land area is a primary decision driver for the 2017 Coastal Master Plan; these options were developed for consideration of the effect of scenario values on coast wide land. The effect of changing storm intensity and frequency on CLARA damage estimates is assessed separately (section 3.2.3).

11.1.1 Option 1 – Baseline Comparison Multi-Phased Approach

This approach is grounded in having a 'baseline' model run intended to represent historical or moderate conditions for comparison to previous outputs or other known conditions. Additional model runs with specific changes to environmental drivers can be performed and compared to the baseline simulation. The intent of this comparison is to determine the effects of change in individual environmental drivers as well as several interactive driver combinations on model outcomes. The first phase of simulations indicates the changes to specific environmental drivers; all other drivers would assume the same values used in the baseline model run. Later phases would change combinations of drivers based on the findings from the first phase and understanding of how environmental factors interact to influence coastal change.

The phased approach provides flexibility to design simulations to examine specific spatial considerations (e.g., some drivers may be expected to have a greater effect on certain regions of the coast), while other simulations would focus on temporal considerations (e.g., some drivers require a full 50-year model run to assess the full breadth of their impacts, but others may not).

In addition, testing drivers individually and collectively in different phases allows environmental drivers that do not show strong influence on the model outputs across their range in the first phase of runs to be eliminated unless there is a reasonable hypotheses that they may have more influence when interacting with a non-baseline value of another driver. A second phase of the analysis could consider values between those used in the first phase and/or could consider hypothesized interactions among changes in drivers (e.g., the effect of changing precipitation/evapotranspiration when SLR is at its highest). The phased approach would allow for testing of key questions or concerns that may arise from the first phase of model simulations in a subsequent phase of simulations.

An example design of the first phase of analysis for this approach is provided in Attachment C2-5 – Options for Sensitivity Analyses Table 1. Reference to "moderate" and "less optimistic" refers to the 2012 Coastal Master Plan scenario values.

11.1.2 Option 2 – Statistically Based Approach

This option includes a matrix of targeted model runs to examine the combined impact of changes in the environmental drivers on the model output as well as to explore the interaction among the environmental drivers. In option 2, the key environmental drivers are organized into three groups. The 64 runs represent each possible mixture of the four combinations for each grouping of drivers (i.e., 4 combinations ^ 3 driver groups = 64), and the intent would be to perform all simulations in a single phase (Table 5). The full set of model runs are listed in Attachment C2-5 – Options for Sensitivity Analyses Table 2. In some cases, the combinations enable exploration of drivers within a group and in other cases spatial variation in outputs may be used to tease out the effects, for instance, of subsidence (which varies spatially) from ESLR (which is a single value coast wide) for each combination. In comparison to option 1, this approach is faster because it does not require iterations. However, it can only explore a specific set of values that must be defined before the analysis begins. Given this, it may be difficult to determine scenario values for each driver since only three values for each driver will be included in the analysis given the limited time available for the analysis. As such, decisions for selecting values for inclusion in the three future scenarios would be drawn from insights gained from these 64 model runs.

Table 5: Experimental matrix design of environmental drivers and four combinations.
Low = the lowest value of the range to be tested; mid = a value in the mid area of the range; high = the highest value of the range to be tested.

Environmental Driver	Combination 1	Combination 2	Combination 3	Combination 4
Precipitation/Evapotranspiration				
Precipitation	Historical (mid)	GENMOM (low)	ECHAM (high)	GENMOM (low)
Evapotranspiration	IWMI - historical (high)	GENMOM (low)	ECHAM (mid)	IWMI - historical (high)
RSLR (Relative Sea Level Rise)				
Subsidence	20% into range (low)	20% into range (low)	50% into range (mid)	75% into range (high)
ESLR	0.22m (low)	0.43m (mid)	0.43m (mid)	0.83m (high)
Tropical Storms				
Frequency (all storms)	-28% (low); 17 storms	-14% (mid); 20 storms	-14% (mid); 20 storms	0% (high); 23 storms
Frequency (major hurricanes)	+13% (low); 8 major	+13% (low); 10 major	+50% (mid); 13 major	+83% (high); 18 major

11.2 Modeling to Identify Scenario Values

The analysis used as a basis for the selection of scenario values was ultimately a hybrid of the approaches described above. It was conducted in two phases in order to first explore the response of land area in the ICM to various combination of environmental driver values, and second to ensure that the scenarios selected represented a spread of landscape changes under Future Without Action Conditions (FWOA). Both phases were necessary as the options described above and the lists of combinations of values shown in the appendices do not necessarily represent combinations of values for use in actual scenarios. Rather, they are designed to explore the sensitivity of model outputs to individual drivers or combinations of drivers. Once candidate values for scenarios were selected, an additional set of analyses was conducted to explore trends over time and to support the selection of three sets of scenario values to move forward.

11.2.1 Sensitivity Analyses

Table 6 shows the values tested with model runs. Run S20 is the 'baseline' model run intended to represent historical conditions. The number of model runs and the values tested were identified based on the time and resources available to conduct the analysis, professional judgment of the potential role of different drivers, and the need to test sensitivity to changes in storm intensity and frequency given that these factors did not influence landscape change in the 2012 Coastal Master Plan modeling.

Table 6: List of the sensitivity runs conducted to assess changes in model outputs of land area in association with changing environmental drivers.

Run ID	Precipitation	Evapotranspiration	Eustatic Sea Level Rise	Subsidence	Number of Storms	Number Of Major Storms
S20	Historical (mid)	Historical (high)	.22m (low)	20% of range (low)	23 (High)	11 (Low)
S21	Historical (mid)	Historical (high)	0.43m (mid)	20% of range (low)	23 (High)	11 (Low)
S22	Historical (mid)	Historical (high)	0.43m (mid)	50% of range (mid)	23 (High)	11 (Low)
S24	Historical (mid)	Historical (high)	.83m (high)	50% of range (mid)	23 (High)	11 (Low)
S26	Historical (mid)	Historical (high)	.22m (low)	50% of range (mid)	23 (High)	11 (Low)
S27	Historical (mid)	Historical (high)	.22m (low)	75% of range (high)	23 (High)	11 (Low)
S30	GENMOM (low)	Historical (high)	.22m (low)	20% of range (low)	23 (High)	11 (Low)
S33	ECHAM (high)	GENMOM (low)	.22m (low)	20% of range (low)	23 (High)	11 (Low)
S36	Historical (mid)	Historical (high)	.22m (low)	20% of range (low)	17 (Low)	8 (Low)
S39	Historical (mid)	Historical (high)	.22m (low)	20% of range (low)	23 (High)	18 (High)
S62	GENMOM (low)	Historical (high)	0.43m (mid)	20% into range (low)	23 (High)	18 (High)
S65	GENMOM (low)	Historical (high)	0.43m (mid)	50% into range (mid)	23 (High)	18 (High)
S68	GENMOM (low)	Historical (high)	0.83m (high)	75% into range (high)	23 (High)	18 (High)
S76	Historical (mid)	Historical (high)	0.43m (mid)	75% into range (high)	23 (High)	11 (Low)
S77	Historical (mid)	Historical (high)	0.83m (high)	20% into range (low)	23 (High)	11 (Low)

Line graphs showing comparisons of land change for several runs including S20 – the 'baseline' run approximating historical conditions – enabled direct evaluation of the sensitivity of the land output to specific changes in values of the environmental drivers. For example, comparison of S20 and S21 (where the environmental drivers other than ESLR are held constant) shows that land area predicted by the model is sensitive to increasing ESLR from the low (S20) to the mid (S21) value (Figure 3).

11.2.1.1 Subsidence and ESLR

Differences in land outputs associated with changing subsidence and eustatic sea level rise were also evaluated (Figure 4). For S22, S26 and S27 in Figure 4 only values for ESLR and subsidence change relative to S20 values. For S68 values for precipation (lower) and storm intensity and frequency (both higher) also change in relation to S20. This accounts for the higher land in S68 in early years of the model run compared to S20.

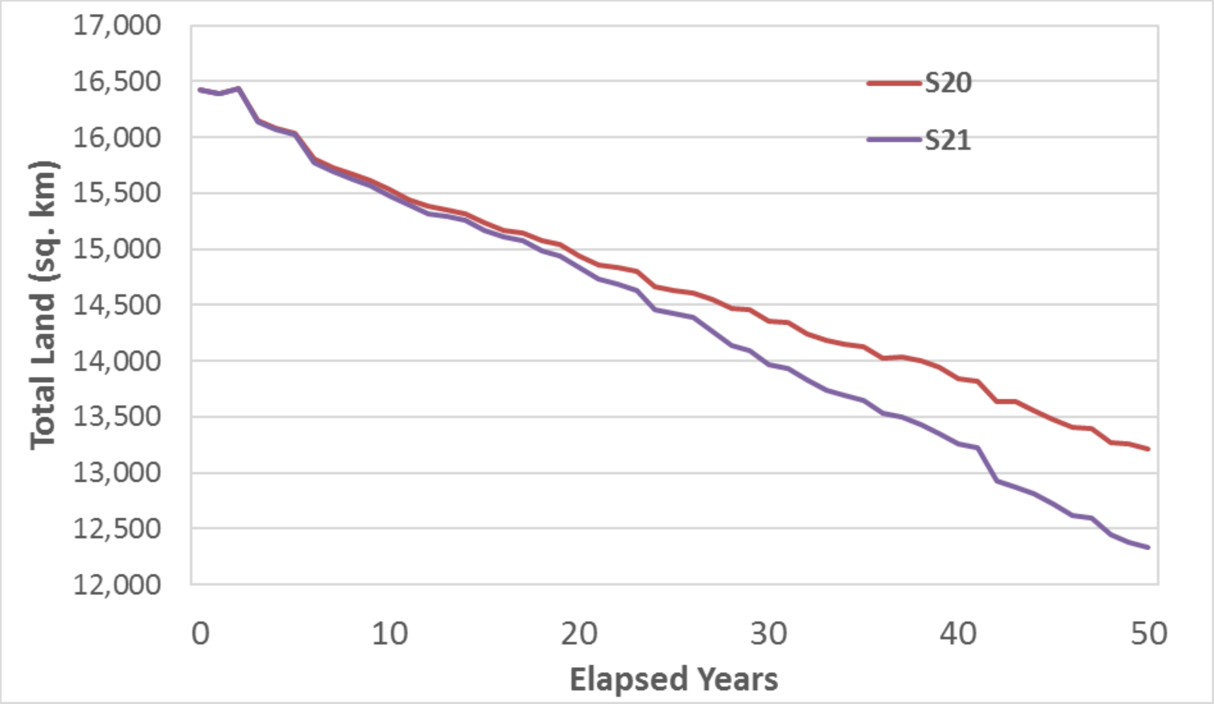

Figure 3: Comparison of coast wide land outputs for S20 (baseline) and S21 (baseline with mid value for ESLR).

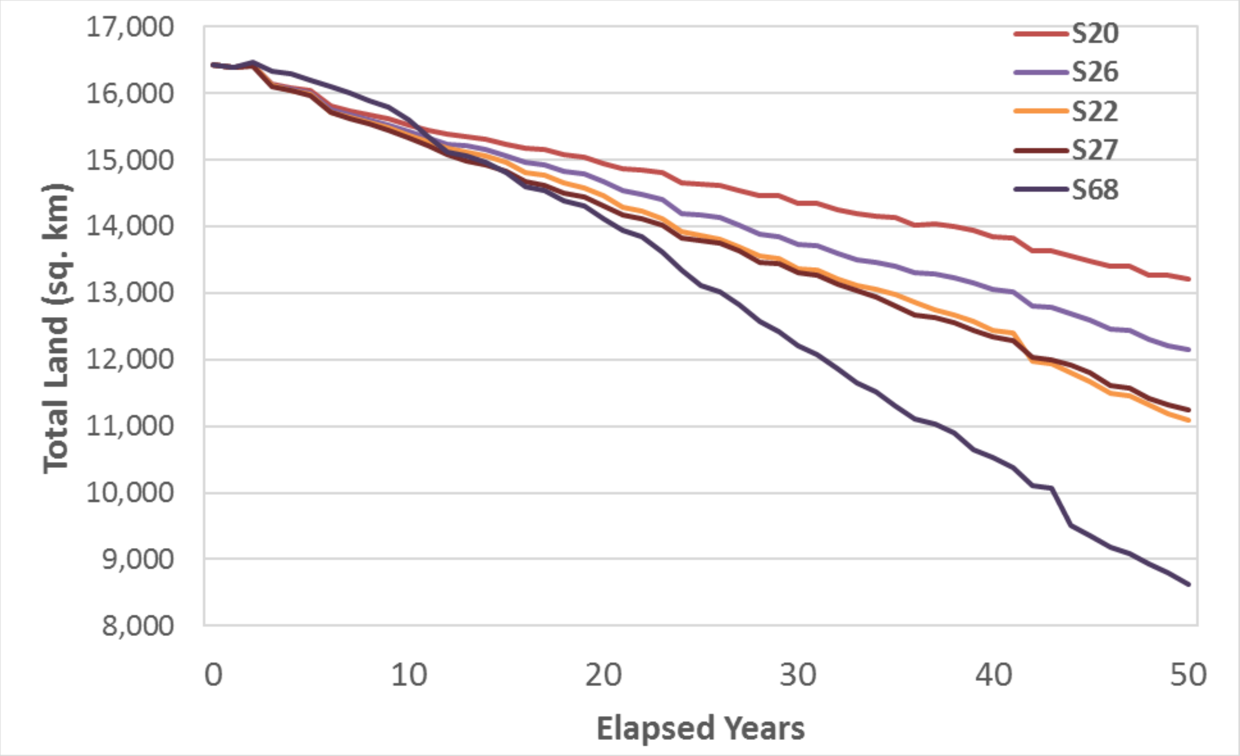

Figure 4: Comparison of coast wide land outputs for model runs with varying subsidence and eustatic sea level rise rates (see text for details). Note extended y-axis compared to Figure 3.

As a result of these analyses, the following combinations of ESLR and subsidence values were selected for further testing in candidate scenarios:

ESLR (m/50yr)	Subsidence
0.43	20% of range
0.63	50% of range
0.83	50% of range
0.63	20% of range
0.63	35% of range

All three values of ESLR tested in the sensitivity runs were selected for inclusion in further analysis. These values are based on extensive literature on future rates of ESLR (Attachment C2-1) and represent the range of conditions considered by the National Climate Assessment (Parris et al., 2012). While the sensitivty runs showed an even higher amount of land loss over 50 years for S68, which included both high ESLR and high subsidence, in general there is less of a consensus regarding future subsidence rates. The plausible range described in Attachment C2-2 is based on expert opinion and while no new coast wide information was available to update the ranges used in the 2012 Coastal Master Plan, some evidence suggests that subsidence rates may decrease over time (Kolker et al., 2011) making the rates toward the high end of the range perhaps less likely to occur. Rather, the subsidence rates selected for further examination span the range considered in the 2012 Coastal Master Plan.

11.2.1.2 Precipitation and Evapotranspiration

While variations in subsidence and ESLR lead to differences in total land area over time, the sensitivity runs demonstrated a much smaller difference in coast wide land when precipitation and evapotranspiration were varied. Figure 5 shows the baseline S20 run against S30 (decreased preciptation relative to S20) and S33 (increased precipation and decreased evapotranspiration relative to S20). Both S30, the drier scenario, and S33, the wetter scenario show less land loss over time than S20. The difference between S30 and S33 at the coast wide scale however is small.

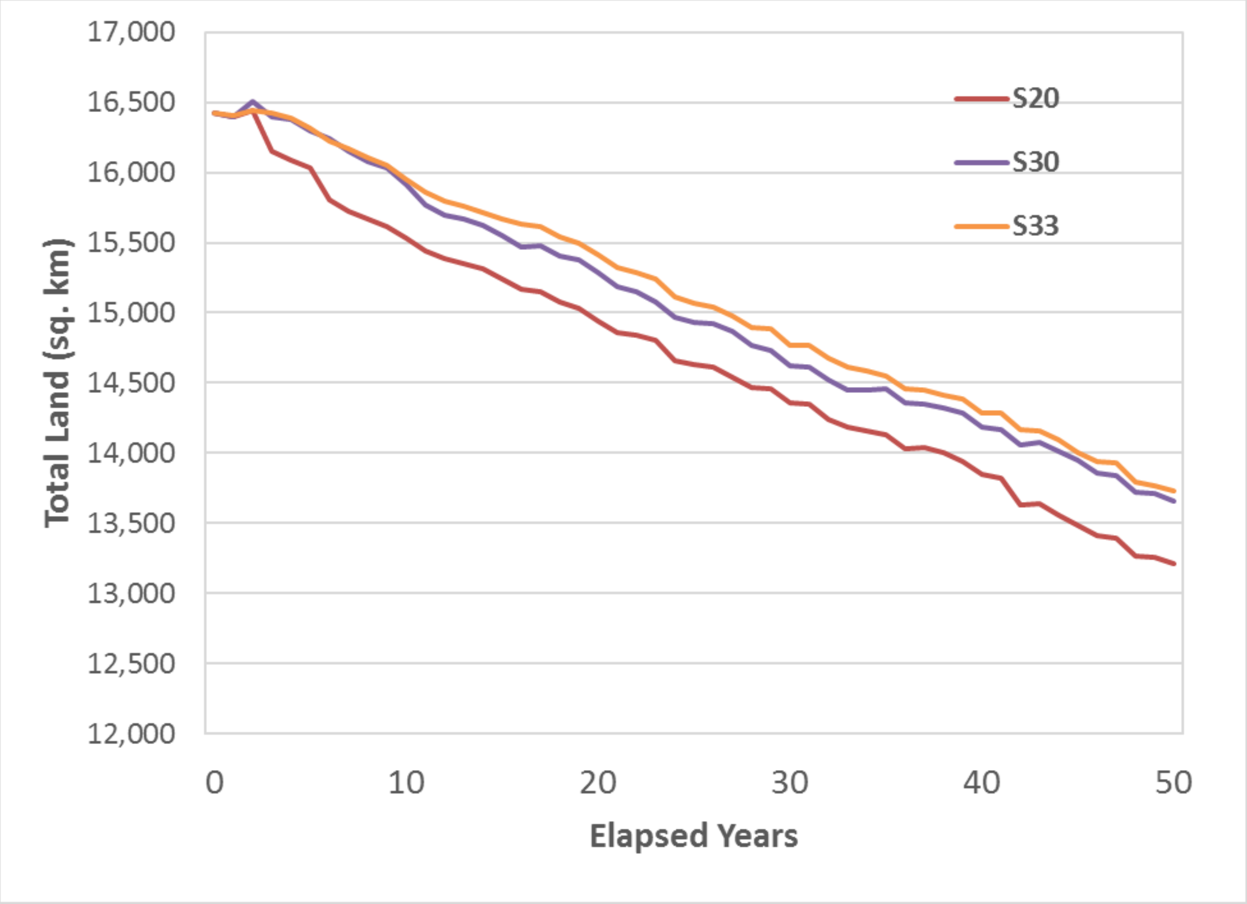

Figure 5: Comparison of coast wide land area for model runs with varying precipitation and evapotranspiration rates. S30 is 'drier' than S20 and S33 is 'wetter' than S20.

To further explore the regional effects of changes in precipation and evapotranspiration, variations over time were examined for selected ecoregions.[2] In addition to assessing long-term trends differences from the baseline run were calculated. Figure 6 shows an example of the

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[2] The coast has been dived into 11 ecoregions, defined by hydrologic boundaries, to facilitate regional comparison of model outputs.

differences between S20 and S33. This graph shows a complex response, that varies by location and over time, to changes in precipitation/evapotranspiration compared to the baseline. While the effect in any individual ecoregion is generally less than 30 km^2, differences in land area can be positive or negative. Note that these are differences from the baseline trend (shown in Figure 3) rather than changes in absolute area within an ecoregion.

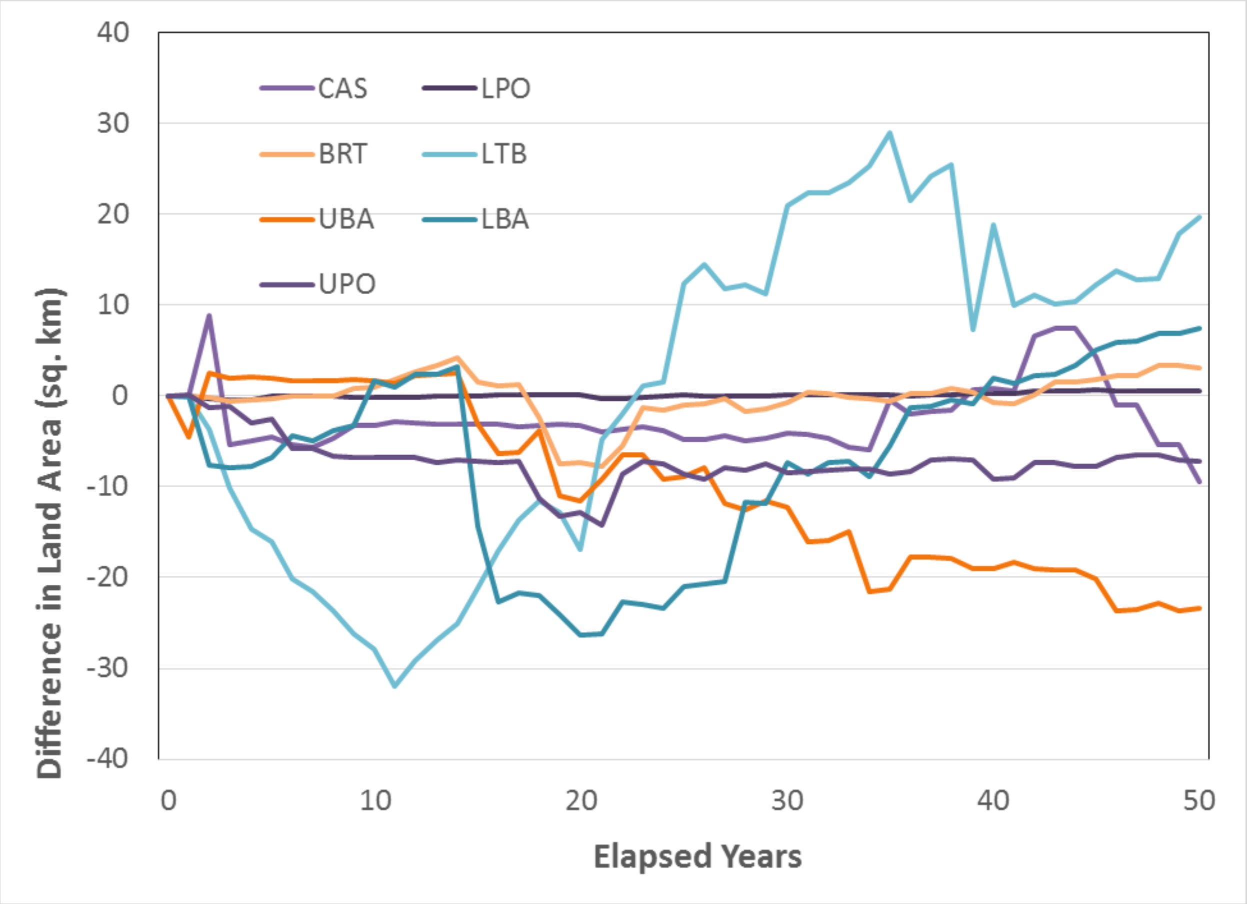

Figure 6: Differences in land area between the baseline run (S20) and a wetter set of conditions (S33) for selected ecoregions. Negative values indicate more land at a time interval in S33 compared to S20. CAS – Calcasieu, LPO – Lower Pontchartrain, BRT – Breton Sound, LTB – Lower Terrebonne, UBA – Upper Barataria, LBA – Lower Barataria, UPO Upper Pontchartrain

After consideration of these and other results of the sensitivity runs, the following values of preciptation and evapotranspiration were selected for further testing using candidate scenarios:

Precipitation	**Evapotranspiration**
>Historical (ECHAM)	<Historical (GENMOM)
>Historical (ECHAM)	Historical
Historical	Historical

Even though the land change effects at the coast wide scale shown in Figure 5 are small, the change away from land loss associated with the 'historical condition' indicates a complex interaction between precipitation and evapotranspiration and landscape change (Figure 6). The values used are derived from global climate modeling, itself the result of the efforts of a broad scientific community (Attachment C2-3). Thus, while the effects of varying precipitation and evapotranspiration may not be large, the inclusion of these variations enables consideration of complex climate-landscape interactions that may occur in the future.

11.2.1.3 Storm Frequency and Intensity

Storm intensity and frequency were also adjusted as part of the sensitivity analysis. In Figure 7, S36 and S39 are identical to S20 except for the storm frequency/intensity – S36 has the lowest storm frequency/intensity, and S39 has the highest frequency of major storms. S36 results in slightly less land loss, and the difference between S20 and S39 is imperceptible at the coast wide scale.

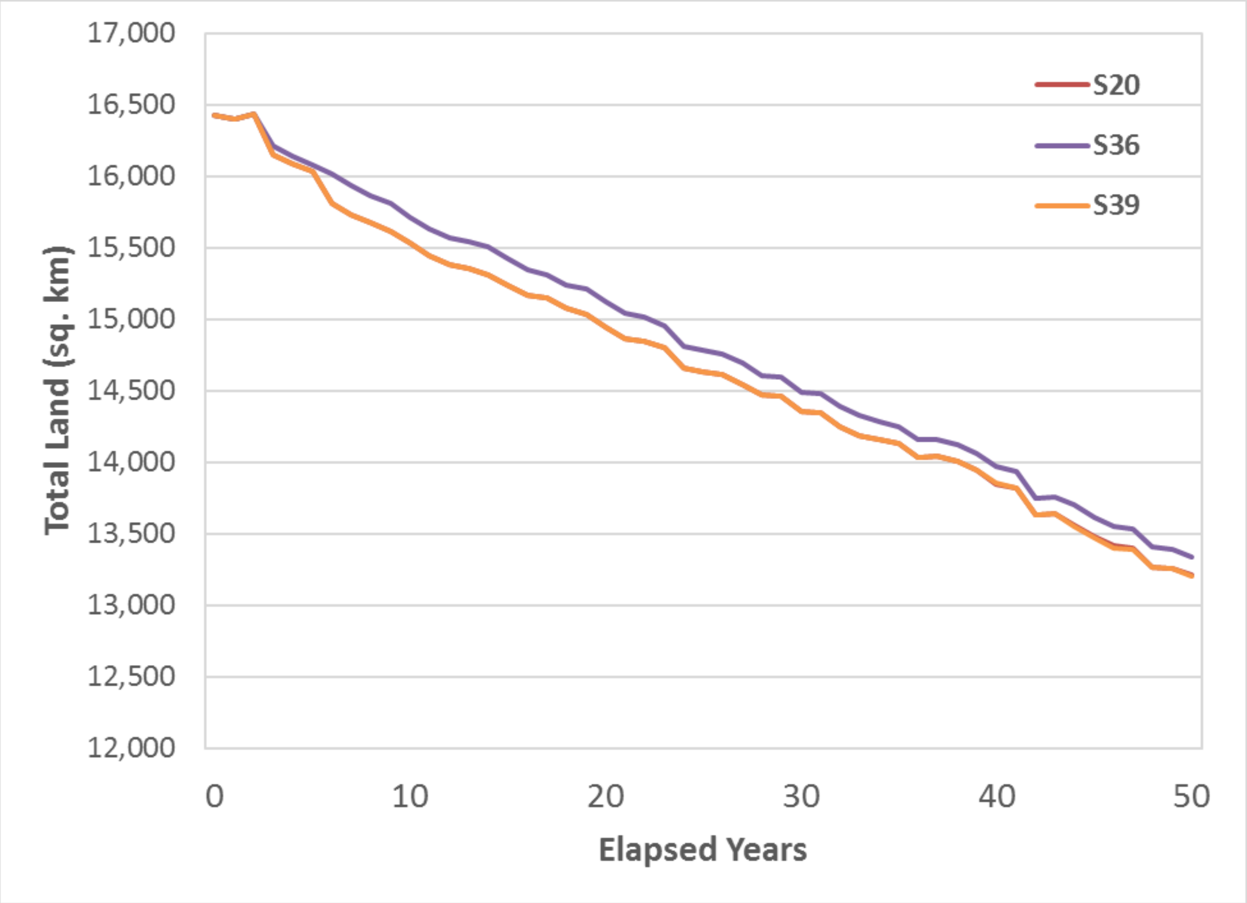

Figure 7: Comparison of coast wide land area for model runs with varying storm frequency and intensity. S36 has fewer total storms and fewer major storms than S20, and S39 has an increased frequency of major storms compared to S20. Note: S20 and S39 total land values are very similar.

The slight changes in coast wide land area associated with increased storms were further explored by comparing S20 and S39 for select ecoregions. Figure 8 shows how there is no difference in land area response until year 21of the analysis when there is a change in the character of the storms included in the runs. In that year a storm in S20 is replaced with a different synthetic storm[3] to represent an increase in the frequency of major storms. Changes in S39 compared to S20 result in more land loss in some ecoregions (e.g., AVB) and less land loss in others (e.g., UTB). In the ICM, storms can erode barrier islands, introduce sediments to marshes, and alter salinity and inundation patterns – effects which can be positive or negative for land area depending on the antecedent conditions. In addition the consequences of the change in storm are not limited to the year in which the storm occurs as changes in land loss alter hydrologic exchange in later years. The next change in storm character occurs in year 34 which triggers a change in land area between S20 and S39 in LTB. Over the 50-year period there are both positive and negative changes in different areas of the coast resulting in very little change at the coast wide scale shown in Figure 7, but a substantial change in some areas.

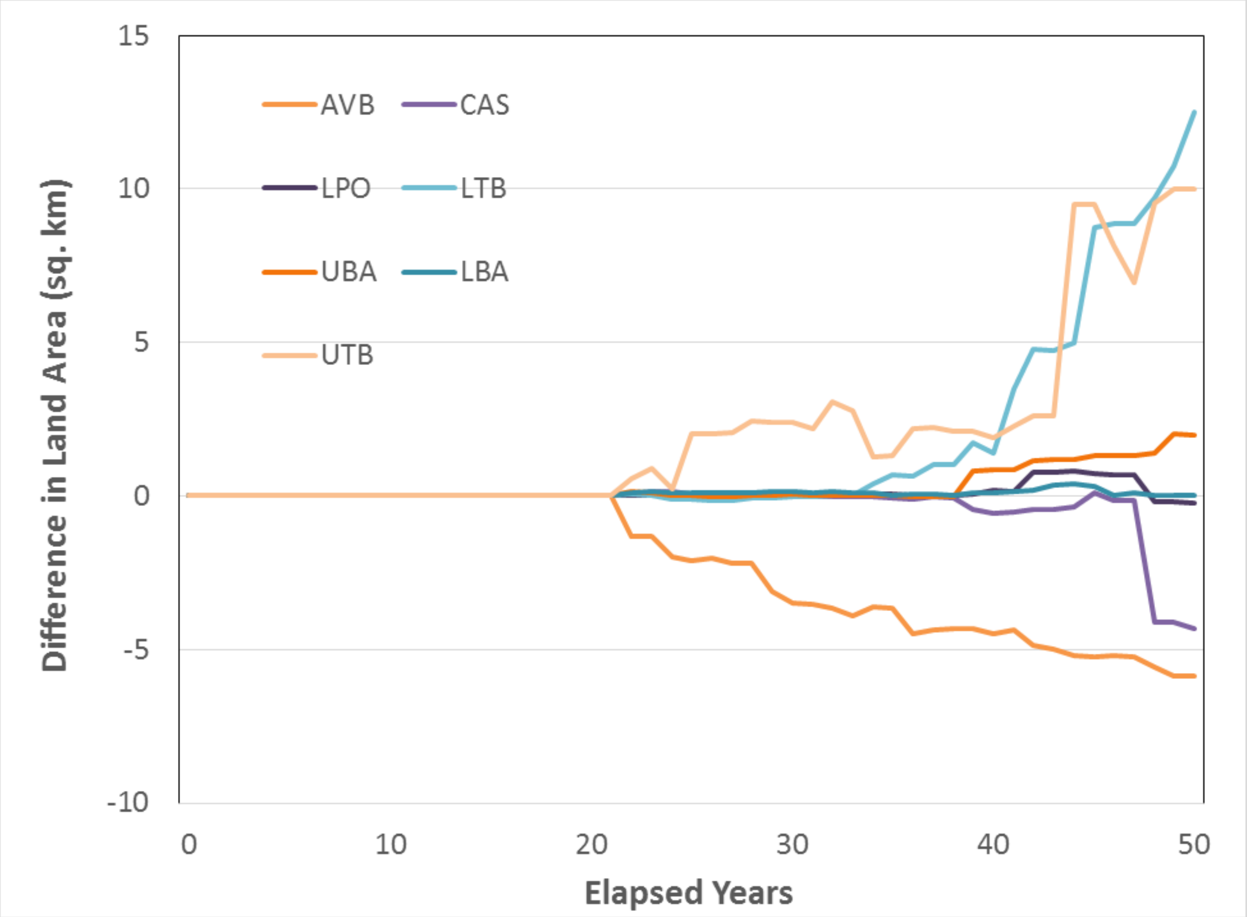

Figure 8: Differences in land area between the baseline run (S20) and an increase in the number of total storms and the frequency of major storms (S39) for selected ecoregions. Negative values indicate more land at a time interval in S39 compared to S20. AVB – Atchafalaya/Vermilion Bay, CAS – Calcasieu, LPO – Lower Pontchartrain, LTB – Lower Terrebonne, UBA – Upper Barataria, LBA – Lower Barataria, UTB – Upper Terrebonne

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[3] See Attachment C3-3 for more details on how synthetic storms were selected for inclusion in the modeling

Examination of the sensitivity of land area to changes in storm intensity and frequency showed that the inclusion (or exclusion) of individual storms over the 50-year period led to substantial local changes in land area but only to a small effect at the coast wide scale. Further inspection of land-water maps indicated that some of these local effects were compartment specific (e.g., the penetration of salt during a storm resulting in land loss). Because the effects are so localized and so sensitive to individual storms, it seems possible that varying the number and intensity of storms among scenarios could subject some projects (e.g., those located in the path of a storm that was included or excluded) to be impacted based on its location rather than its restoration characteristics. While this remains an issue to be carefully evaluated even if the storm set stays the same among the scenarios, varying storms by scenario could make the interpretation of project results challenging. Thus, the decision was made not to vary storm intensity and frequency in the landscape analysis.

11.2.2 Evaluation of Candidate Scenarios

Five candidate scenarios were selected for testing to inform the selection of the three environmental scenarios to be used in the 2017 Coastal Master Plan (Table 7). Due to the small variation on coast wide land associated with variation in precipitation and evapotranspiration, only three combinations were tested. These were combined with five combinations of values for eustatic sea level rise and subsidence.

Table 7: Values used in the five candidate environmental scenarios.

Scenario	Precipitation	Evapotranspiration	ESLR (m/50yr)	Subsidence
1	>Historical (ECHAM)	<Historical	0.43	20% of range
2	>Historical (ECHAM)	Historical	0.63	50% of range
3	Historical	Historical	0.83	50% of range
4	>Historical (ECHAM)	Historical	0.63	20% of range
5	>Historical (ECHAM)	Historical	0.63	35% of range

The results of the candidate scenario testing are shown in Figure 9. As expected based on the sensitivity analysis, S03, with the highest ESLR and the highest subsidence value, shows the greatest decrease in land area. S01 with the lowest ESLR and subsidence values shows the lowest coast wide land loss.

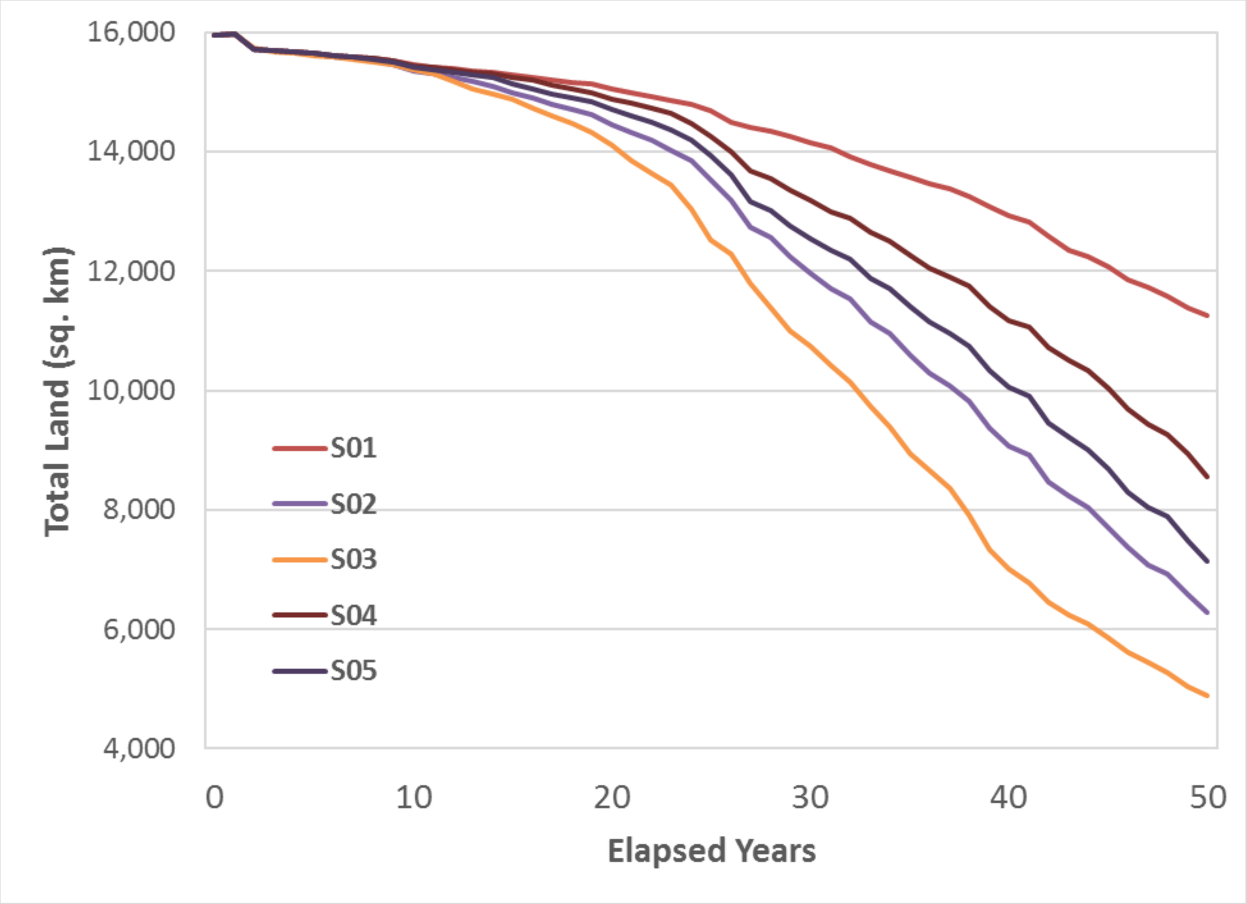

Figure 9: Coast wide land area under Future Without Action for the five candidate scenarios (see Table 7 for drivers included in each).

11.2.3 Varying Storm Frequency and Intensity in CLARA

The CLARA model implements uncertainty in future storminess using environmental drivers, one representing the overall frequency of hurricanes impacting the study region and the other representing the average intensity of those storms. Future scenarios are defined by specifying changes in those two characteristics, relative to a baseline of current conditions. By contrast, the ICM models the overall frequency of hurricanes with no change from the historical record and specifies the frequency of major storms (those with sustained winds of greater than 100 knots). Separately varying the frequency of all storms and the frequency of major storms implies a change in the average intensity of storms included in the analysis.

As such, the implementations of future storminess in the CLARA and ICM models are related. Test runs of the ICM showed that a scenario assumption with the overall frequency of storms declining by 28% and the frequency of severe storms within the decreased total increasing by 13% over the 50-year simulation period showed little change in the net area of land across the coast (although there were local changes). Empirical analysis of the National Hurricane Center

Data set[4] indicates that this is equivalent in CLARA to a 28% decline in storm frequency combined with a 10% increase in average storm intensity.

Sensitivity testing suggests that modeling variation in both storm frequency and intensity is important for identifying potential variation in the performance of risk reduction projects. Coast wide estimates of expected annual damage (EAD) were generated using test data from the Year 50, 2012 Coastal Master Plan Less Optimistic landscape, varying storm frequency by -5%, 0%, and +5% relative to the historical frequency, and varying average storm intensity by 0%, 10%, and 20%. (Note that the 0%/0% case is equivalent to seeing no change in storminess compared to historical conditions, and the 5%/20% case is equivalent to the change in storminess assumed by the Less Optimistic scenario in 2012.)

Examining the elasticity of damage with respect to the parameters (i.e., the change in EAD resulting from a percentage change in storm frequency or average intensity) reveals some key differences:

1. Damage elasticity with respect to average storm intensity appears approximately constant, with a 10% increase in average intensity producing an 8% increase in EAD. The elasticity with respect to frequency varies, though; moving from -5% to 0% increases coast wide EAD by about 4.6%, but going from 0% to 5% increases EAD by about 8.7%.
2. Changes in storm intensity have a much more pronounced effect on EAD for areas within the Hurricane Storm Damage Risk Reduction System (HSDRRS), relative to other areas. A 10% increase in intensity increases EAD by about 15% for points on the East Bank of New Orleans, and 20% on the West Bank of New Orleans, compared to increases of 5.5% in other enclosed areas and 6.5% in unenclosed areas. Changes in storm frequency, on the other hand, produce approximately the same change in EAD for enclosed and unenclosed points.

Table 8 summarizes the above points by showing the EAD estimated by enclosed location and future storm frequency and average intensity for the nine cases analyzed. Coast wide totals are also provided In Table 9. Changing the frequency and intensity values for future scenarios will thus reveal differential performance in structural and nonstructural risk reduction projects, depending on what type of area they are designed to protect.

Table 8: EAD as a Function of Changes in Storminess.

		Future Average Storm Intensity		
Enclosed Status	**Future Storm**	**No**	**+10%**	**+20%**
East Bank HSDRRS	-5%	$1,996M	$2.298M	$2,641M
	No Change	$2,086M	$2.415M	$2,789M
	+5%	$2,262M	$2.589M	$2,986M

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[4] The National Hurricane Center maintains HURricane DATabases (HURDAT)that contain details on tropical storms, that have occurred within the Atlantic Ocean since 1851.

		Future Average Storm Intensity		
Enclosed Status	**Future Storm**	**No**	**+10%**	**+20%**
West Bank HSDRRS	-5%	$111M	$131M	$162M
	No Change	$119M	$144M	$177M
	+5%	$126M	$148M	$189M
Enclosed, Non-HSDRRS	-5%	$1,550M	$1,637M	$1,724M
	No Change	$1,628M	$1,713M	$1,806M
	+5%	$1,759M	$1,870M	$1,996M
Unenclosed	-5%	$11,147M	$11,859M	$12,657M
	No Change	$11,645M	$12,400M	$13,208M
	+5%	$12,615M	$13,517M	$14,474M

Table 9: EAD as a Function of Changes in Storminess - Coast wide Summary.

	Future Average Storm Intensity		
Future Storm Frequency	**No**	**+10%**	**+20%**
-5%	$14,805M	$15,925M	$17,184M
No Change	$15,479M	$16,672M	$17,980M
+5%	$16,762M	$18,124M	$19,615M

12.0 Selection of Environmental Scenarios

Based on the analysis and testing described above, three environmental scenarios have been selected for use in the 2017 Coastal Master Plan. The values for these scenarios are shown in Table 10.

Table 10: Characteristics of the Environmental Scenarios to be used in the 2017 Coastal Master Plan.

Scenario	**Precipitation**	**Evapotranspiration**	**ESLR (m/ 50yr)**	**Subsidence**	**Overall Storm Frequency**	**Average Storm Intensity**
	Used in ICM				Used in CLARA	
Low	>Historical	<Historical	0.43	20% of range	-28%	+10.0%
Medium	>Historical	Historical	0.63	20% of range	-14%	+12.5%

Scenario	Precipitation	Evapotranspiration	ESLR (m/ 50yr)	Subsidence	Overall Storm Frequency	Average Storm Intensity
	Used in ICM				Used in CLARA	
High	Historical	Historical	0.83	50% of range	0%	+15.0%

The values for use in the ICM were selected to ensure that there was a range of consequences, in terms of coast wide land area, across the three scenarios. The Low, Medium, and High Scenarios correspond to S01, S04, and S03 in Figure 9. CLARA will model variability in the future storm frequency and average intensity to better explore the differential performance of projects under a range of future conditions. Values for each scenario used in CLARA were chosen to explore a range of plausible future changes in storm frequency and average intensity.

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Chapter 3: Modeling Overview

This chapter provides an overview of the modeling tools used to inform the development of the 2017 Coastal Master Plan. Contents include:

- Summary overviews of subroutines that make up the Integrated Compartment Model (ICM), focusing on major changes since the 2012 Coastal Master Plan modeling effort. ICM subroutines include:
    - Hydrology
    - Morphology
    - Barrier islands (BIMODE)
    - Vegetation
    - Habitat suitability indices (HSIs)
- Updates to the boundary conditions used for hydrodynamics, landscape, and explicit tropical storm events
- Other models utilized in the 2017 Coastal Master Plan modeling effort, including:
    - Ecopath with Ecosim (EwE) for dynamic fish and shellfish community modeling
    - ADCIRC for tropical storm surge and waves
    - Coastal Louisiana Risk Assessment (CLARA) model for assessing risk and potential damage from tropical storms
- An overview of the ICM calibration procedure
- An overview of the 2017 Coastal Master Plan data management strategy

14.0 Overview of the Integrated Compartment Model (ICM)

The Integrated Compartment Model (ICM) is a computationally efficient, coast wide mass balance model that can be used for a large number of 50-year simulations in a reasonable timeframe. It combines the previously independent models (eco-hydrology, wetland morphology, barrier shoreline morphology, and vegetation) used in the 2012 Coastal Master Plan (see Chapter 1 and CPRA, 2012 – Appendix D), and includes a number of physically-based improvements. Integrating individual models removed the inefficiency of manual data hand-offs required during the 2012 Coastal Master Plan effort (due to independent models with no internal linkages) and the potential human error that may occur during the transfer of information from one model to another. The ICM serves as the central modeling platform for the 2017 Coastal Master Plan to analyze the landscape performance of individual projects and alternatives (groups of projects) for a variety of future environmental scenarios for up to 50 years. Hydrodynamics, morphology, and vegetation are now dynamically linked with annual feedbacks. Information transfer between models was only possible at year 25 during the 2012 effort. This led to an inability of one 2012 model (e.g., vegetation) to reflect change in shorter-term processes arising from changes in related parameters projected by another model (e.g., morphology). For example, in 2012 the morphology and vegetation subroutines only exchanged information at year 25, if an area converted to a more saline tolerant vegetation type between model years 25 and 50 in the vegetation model, the morphology model was unaware of this transition. Consequently, it may have forecast the collapse of fresh marsh areas that would have converted to another vegetation type, thereby overestimating coastal wetland loss. The increased frequency in data exchange among ICM subroutines reduces those types of errors and improves the quality of model results.

Key ICM outputs include hydrodynamic variables (e.g., salinity and water level), water quality (e.g., total suspended solids [TSS] and nitrate [NO3]), changes in the landscape (e.g., land area and elevation change, including the barrier islands), and changes in vegetation (e.g., location and type). Nineteen new or improved habitat suitability indices (HSIs) have also been integrated into the ICM; however, they are considered terminal outputs as there are no feedbacks to the other ICM subroutines.

15.0 Hydrology Subroutine

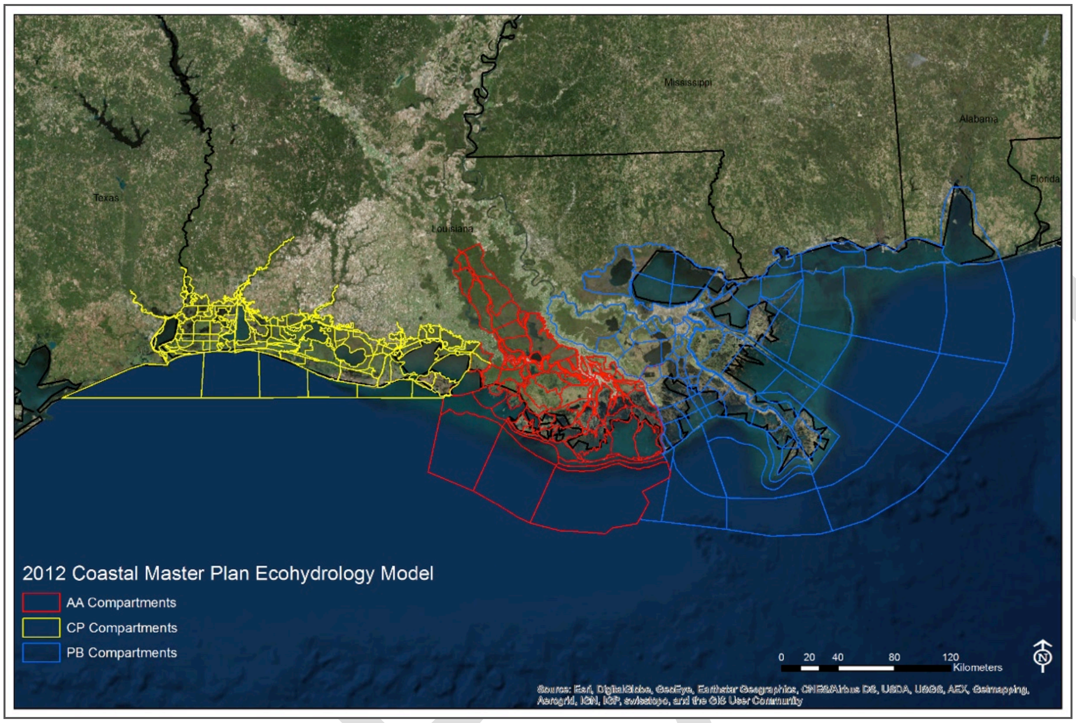
The 2017 Coastal Master Plan hydrology subroutine of the ICM is a mass balance compartment model used to predict water level, salinity, sediment, and other water quality constituents for 50 years into the future. It is integrated with feedbacks to the morphology and vegetation subroutine. The 2017 hydrology subroutine was built upon the 2012 Coastal Master Plan eco-hydrology model. The spatial resolution of the compartments was increased and new processes were developed and included. The following is a brief summary of key changes since 2012. For additional details regarding this subroutine and how it is integrated into the ICM, refer to Attachment C3-1 – Sediment Distribution and Attachment C3-22 – ICM Integration.

15.1 Model Design

The 2012 eco-hydrology modeling used a mass balance approach whereby the system is characterized using a set of compartments connected by links that control the flow of constituents among the compartments. Specifically, three mass balance, link node, compartment models (Meselhe et al., 2013) were used covering different regions of the coast: (1) Atchafalaya-Terrebonne (AA), (2) Chenier Plain (CP), and (3) Pontchartrain-Barataria (PB) (Figure 10). The PB model was developed in the Formula Translating (Fortran) system programming language using the multi-type compartment design that subdivides a hydrological compartment into upland, marsh, and open water subcompartments. The AA and CP models were developed in the Berkeley Madonna equation solver governed by the same hydrodynamic equations but using the single-type compartment design, whereby a compartment is composed of only a channel, marsh, or open water rather than being subdivided (Meselhe et al., 2012). Figure 11 shows a schematic of the multi-type and single-type compartment designs. Considering the timeline for model development for the 2012 coastal master plan, existing models were used where available (e.g., PB). Although there were differences among the models used for different parts of the coast, they were standardized to the extent possible, and any differences were determined to be negligible in terms of producing 50 year model outputs. The 2017 hydrology subroutine adopted the PB Fortran multi-type compartment design. Fortran was used for the 2017 effort because it is a more flexible coding language with more versatility for integrating model code when compared to Berkeley

Madonna. The PB multi-type compartment set up was chosen over that used in the AA and CP regions of 2012 because PB was already coded in Fortran.

The new hydrology subroutine was developed as a single coast wide model (Figure 12) but can be subdivided into the AA, CP, and/or PB regions if only one or two of the regions are required for a particular simulation. Since the 2017 hydrology subroutine has adopted the PB region's design, only the differences in 2017 hydrology subroutine, compared to 2012 eco-hydrology model, are discussed in this overview.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Figure 10: 2012 Coastal Master Plan eco-hydrology model compartments and domains.

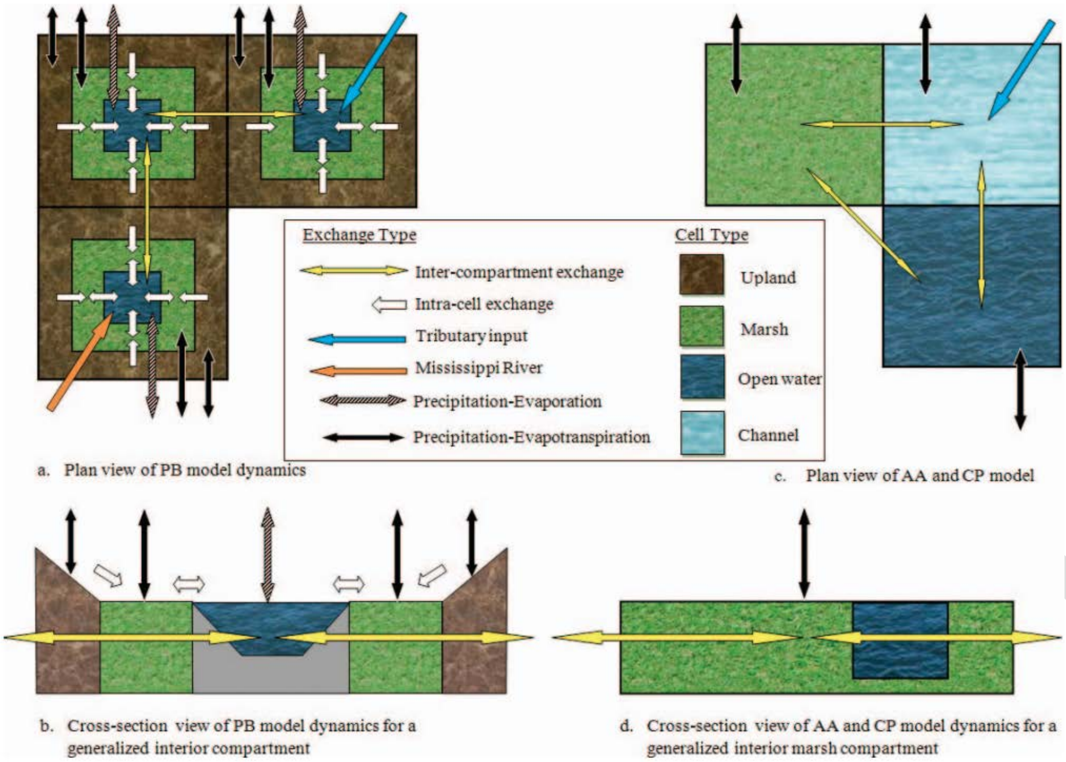


Figure 11: Multi-type (left) and single-type (right) compartment designs.

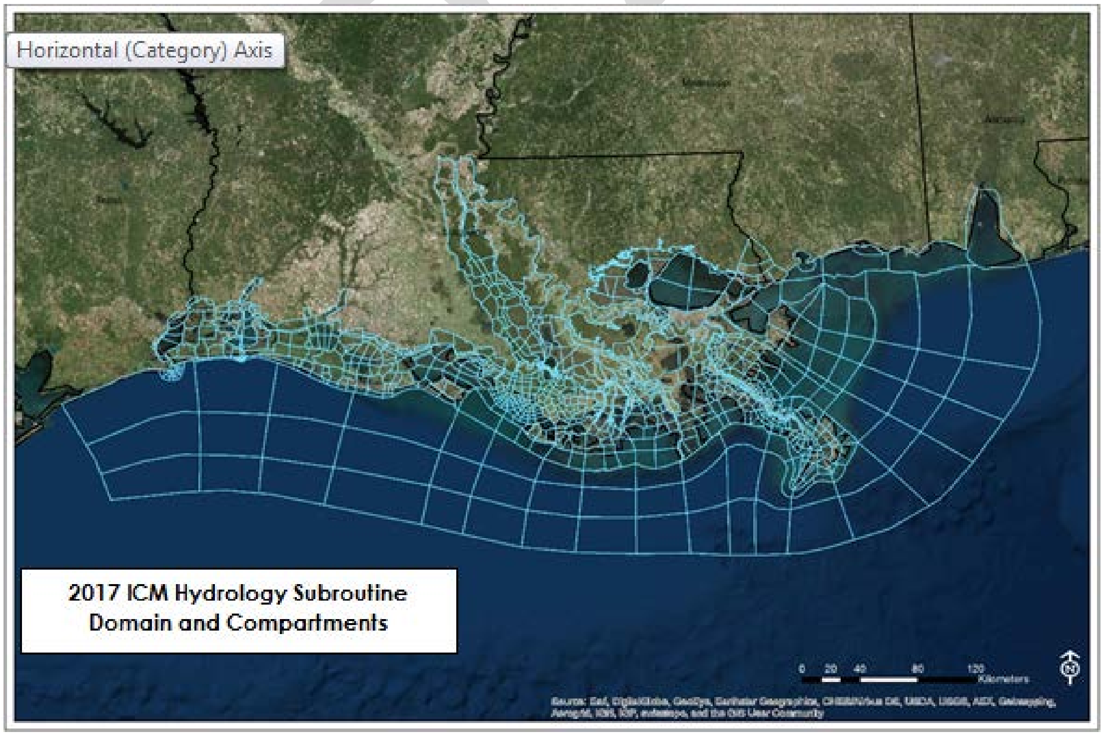


Figure 12: 2017 Coastal Master Plan Integrated Compartment Model (ICM) – hydrology subroutine compartments and domain.

15.2 Model Domain

For 2017, the southern boundary of the model domain was shifted further offshore to approximately the 30 m contour to reduce variation in salinity so a constant offshore boundary salinity could be applied and to have all the regions the same "distance" offshore. The east and west boundaries had negligible change, and the northern boundary in the AA region was shifted north to include the entire Atchafalaya Basin area between the East Atchafalaya Basin Levee and the West Mississippi River and Tributaries Levee. See Figure 10 and Figure 12 for the spatial extent of each model domain.

15.3 Compartments

Spatial resolution of the compartments in all three regions was increased compared to the 2012 effort to better represent coastal processes, such as sediment distribution (Table 11). This was made possible due to advances in computational processing power. Uncertainty in sediment distribution dynamics increases as the size of the hydrology compartments increase. Excluding large offshore hydrology compartments (which are included in Table 11), compartments specifically in the area of the modeling domain in which most diversions are modeled were reduced from an average size of 180 km^2 in the 2012 effort to 20 km^2 for the 2017 effort. It is in these compartments that accurate sediment distribution is most critical for predicting project benefits. The increased spatial resolution in these areas enhances accuracy associated with projected diversion land area benefits

Compartments in the AA and CP regions were delineated to convert them from the single-type to the multi-type compartment design. Unlike the 2012 eco-hydrology model, the 2017 hydrology subroutine now has coast wide coverage of multi-type compartments. Overall, there are a total of 946 compartments across the coast in the 2017 hydrology subroutine, compared to 403 in the 2012 eco-hydrology model.

Table 11: Summary of hydrology compartments per region and model; values include all compartments in the model domain, including large offshore compartments.

	2012 Eco-hydrology Model		2017 ICM Hydrology Subroutine	
Region	**Total**	**Area Ranges in km^2 (average)**	**Total**	**Area Ranges in km^2 (average)**
AA	165	0.04 – 3361 (121)	388	1.02 – 1477 (69)
CP	149	0.44 – 1844 (86)	245	0.40 – 2833 (123)[1]
PB	89	2.2 – 5844 (716)	313	1.84 – 3187 (160)

[1] average area increased as a result of the additional, large offshore compartments for the CP region

15.4 Link Network

The ICM's hydrology subroutine utilizes a link-node type of hydraulic exchange. Each node of the subroutine is a hydrologic compartment, which consists of open water, marsh, and (optionally) upland areas. The links represent the hydraulic pathways (bayous, bay inlets, canals, marsh areas, etc.) connecting each compartment to neighboring compartments. All modeled processes (rainfall/runoff, sediment distribution, water quality sources/sinks, wave generation, etc.) take place within the node/compartment, and the link network is used to convey flows and constituents between compartments.

Both the 2012 eco-hydrology model and the 2017 hydrology subroutine link networks consist of intracompartmental and intercompartmental link types. The intracompartmental link types used in the 2017 hydrology subroutine consist of rainfall/runoff processes in upland, marsh, and open water areas, as well as exchange flow between the open water and marsh areas within a compartment. Of the intercompartmental link types, both the 2012 and 2017 versions include channel, lock, saltwater barrier or tide gate, and pump link types. The 2017 hydrology subroutine additionally includes weir; orifice, culvert, or bridge; overland marsh; ridge or levee; and dormant link types. Dormant links are inactive links in the model that become activated only after certain criteria are met during the model simulation. Intercompartmental links connect the open water portion of one compartment to the open water portion of a neighboring compartment, with the exception of the overland marsh links. Overland marsh links allow for overland flow across marsh areas, and connect the marsh area of one compartment to the marsh area of a neighboring compartment.

Although both 2012 and 2017 versions include lock link types, there was an update to the lock operations in 2017. The 2012 eco-hydrology model lock operations were either operated based on the recorded schedule, or not operated and remained open 100% of the time. The 2017 hydrology subroutine can operate locks based on differential stage, hourly schedule, downstream stage, downstream salinity, or downstream stage and salinity.

In addition to the hydraulic control rules that can now be simulated via the aforementioned operational regimes; weirs, orifices, culverts, and tide gates were also added to better represent the highly engineered hydrology of Coastal Louisiana within the ICM's hydrology subroutine.

Overland marsh and ridge or levee link types were added to the 2017 hydrology subroutine to allow for the propagation of extreme water levels during a major riverine flood and/or tropical system's storm surge.

Dormant links allow the building of a delta or breaching of a barrier island. For deltas, they were added to the fan-like compartment layouts in areas of actively growing deltas and areas of potential delta growth (e.g., from sediment diversion projects). As sediment is deposited and accumulates on a compartment bed, the open water link invert elevation increases, resulting in a decrease of the link's flow capacity (i.e., cross-sectional area). Once the capacity of the open water link is reduced to be equal to the capacity of the regime channel (i.e., the minimum cross-sectional area required to facilitate the specified diversion flow rate and particle size), the original open water link is deactivated and the dormant link – with dimensions of the regime channel – is activated. Additionally, sediment deposition will no longer occur in this compartment and is instead pushed downstream to the next compartment. For barrier islands, a dormant link is added to each island to be activated if an island breach occurs, forming an inlet and allowing exchange of water from offshore to the bay.

15.5 Compartment and Link Attributes

The 2012 eco-hydrology compartment bed elevations and link invert elevations were calculated using the Digital Elevation Model (DEM) developed by United States Geological Survey (USGS) for the 2012 Coastal Master Plan. The 2017 hydrology subroutine compartment bed elevations and link invert elevations were calculated using the updated 2017 Coastal Master Plan DEM. For additional information about this DEM, please refer to Attachment C3-27 – Landscape Data.

For additional information regarding compartment delineations and hydrodynamic links, refer to Attachment C3-22 – ICM Integration.

15.6 Governing Equations

The hydrodynamic formulations used in the 2017 hydrology subroutine are unchanged from 2012 eco-hydrology, as these were based on well-known and widely accepted hydrodynamic principles. These formulations can be found in the 2012 Coastal Master Plan report Appendix D-1 (Meselhe et al., 2012).

An extensive effort to improve the simulation of sediment distribution among and within hydrology compartments was undertaken for 2017. In 2012, a single sediment accumulation value was calculated for each compartment, and sediment was distributed within a compartment based on a sediment distribution probability surface, which was based upon the weighting of factors such as distance from sediment source, frequency of inundation, and distance from water bodies. Also, the 2012 eco-hydrology model assumed that open water bottoms (i.e., the bed) have an endless supply of sediment for resuspension, while the 2017 hydrology subroutine assumes a maximum TSS concentration and a limit to the amount of erodible material available for resuspension. In both the 2012 PB eco-hydrology model and the 2017 hydrology subroutine, the intracompartment exchange between the open water and marsh allowed sediment transfer to the marsh surface. In the 2017 modeling effort, an additional source of sediment (from marsh edge erosion) is included in the morphology subroutine; refer to the morphology section below for additional information.

Both the 2012 and 2017 versions of the model code distribute sediment throughout the model domain to account for tropical storms. The 2012 eco-hydrology model did not simulate tropical storms explicitly, and therefore, to schematize the process of sediment distribution from tropical events to the landscape, 1000 g/m^2/year of sediment was assumed delivered to each hydrology compartment (Couvillion et al., 2013) for the duration of the model run. The 2017 hydrology subroutine explicitly simulates tropical storm events by applying elevated water levels (i.e., storm surge) at the offshore boundary and the storm’s wind field temporally and spatially along the storm’s path. Therefore, the sediment from tropical storms is delivered from the offshore compartments to the marsh as sediment is resuspended from the bed due to higher wave energy, and the marsh is inundated due to higher water levels.

The 2017 Coastal Master Plan water quality constituents are predicted as part of the hydrology subroutine. The predictions are based on advection-diffusion equations of chemical species. Source/sink terms are included to account for mass transfers due to chemical kinetic processes. Water quality parameters, including total suspended solids (TSS), salinity (SAL), water temperature (TMP), nitrate + nitrite nitrogen (NO3), ammonium nitrogen (NH4), total inorganic phosphorus (TIP), dissolved organic phosphorus (DOP), dissolved organic nitrogen (DON), blue-green algae (ALG), detritus (DET) are simulated. The ICM water quality formulations are unchanged from the 2012 Coastal Master Plan AA and CP regional models. These formulations can be found in the 2012 Coastal Master Plan report Appendix D-1 (Meselhe et al., 2012).

16.0 Morphology

The 2017 morphology subroutine tracks relative elevation and uses the elevation (accretion), along with water level and salinities from the hydrology subroutine to assess changes in wetland area. The fate of a particular area of land is partly determined by its ability to maintain or build to an elevation (relative to water level) suitable for wetland vegetation establishment or persistence under varying scenarios of sea level rise, subsidence and restoration efforts.

The 2017 morphology subroutine builds upon portions of the 2012 Coastal Master Plan wetland morphology model (Couvillion et al., 2013). Improvements include a number of refinements to the coding and integration with the hydrology and vegetation subroutines in the ICM. The 2017 morphology subroutine makes projections at the 30 m x 30 m grid cell resolution of wetland area, landscape configuration, vertical accretion and elevation, compared to 500 m x 500 m which was used in 2012. As the output of this subroutine includes land area change, which is critical to the formulation of restoration and protection planning, its accuracy is of high importance. Understanding the changes that have been made to the data layers and processes since the 2012 Coastal Master Plan version of the model is also important for understanding the modeling results.

The baseline datasets were updated for the 2017 modeling effort. The 2012 models were initialized with datasets from a circa 2010 base period. The coastal landscape has changed since 2010 due to ongoing coastal process such as wetland loss, gain, and coastal restoration and protection efforts. Therefore, several input datasets were updated to reflect a 2014 starting period for the 2017 Coastal Master Plan effort. These include a late 2014 (November) land and water composition configuration dataset. The integrated bathymetry/topography dataset and the base vegetation distribution layer used for model initialization were also updated. These updated layers ensure that any changes that have taken place between 2010 and 2014, including coastal restoration projects, are appropriately considered in the model runs.

Regarding model processes, one of the least robust aspects of the 2012 modeling effort was the sediment distribution. To improve this, a number of changes were made as described in the hydrology subroutine section, and an extensive literature review was conducted and alternative methodologies considered. In addition to the changes detailed above, sediment accumulation is now calculated in three distinct zones: marsh edge, interior marsh, and open water. Sediment accumulation is also now calculated for sand, silt, and clay separately. Resuspension for silt and clay is calculated based on excess bed shear (bed shear minus critical shear) and consolidation time. The flocculation of clay is a function of the salinity. The sand accumulation rate in open water is calculated based on the difference between the sand inflow and the sand transport capacity. The flow exchange between the open water and the marshes is calculated using the Kadlec-Knight formula, in which flow is a function of vegetation density, width of the flow path, inundation depth, and the distance between stage locations. Finally, resuspension of sediment in the marshes does not occur under non-tropical storm conditions as per Christiansen et al., (2000). All of these improvements serve to reduce uncertainties in the model outputs that were previously attributed to an inability to realistically distribute sediment within a hydrology compartment.

Another important improvement that has been incorporated in the 2017 Coastal Master Plan modeling effort is the inclusion of marsh edge erosion. In 2012, marsh edge and shoreline erosion was not directly calculated, but was rather incorporated through the use of a background change rate calculated from historical land change data. Losses due to erosion were forced upon the landscape through the use of an erosion probability surface and a background land change incorporation sub-model. For the 2017 effort, spatially variable erosion rates were calculated for all shorelines that experienced erosion during a 2004-2012 observation period. The morphology subroutine calculates the number of pixels of shoreline that should be eroded for any given modeling period based upon these historical rates. Those areas are then converted from land to open water in the ICM. These spatially variable rates, calculated from high resolution historical imagery represent an improvement from the background change rate method previously used.

For additional information on how the morphology subroutine is integrated in the ICM, refer to Attachment C3-22 – ICM Integration.

17.0 Barrier Islands (BIMODE)

This section summarizes the changes made in the Barrier Island Model (BIMODE) subroutines between the 2012 and 2017 Coastal Master Plan modeling efforts. The 2012 version is documented in Appendix D-3: Barrier Shoreline Morphology Technical Report (Hughes et al., 2012), and a more complete description of the 2017 version of BIMODE is provided in Attachment C3-4 – Barrier Island Model Development (BIMODE).

In general, BIMODE is a planning level model separated into six island regions: Isles Dernieres, Timbalier, Caminada Headland and Grand Isle, Barataria, Breton Island, and Chandeleur Island. It is capable of predicting barrier island evolution for 50 years. It is physically based and includes both long-shore and cross-shore processes and has the ability to explicitly capture the effects of tropical storm events on overwash. BIMODE interacts with other ICM subroutines, including dune, swale, and back barrier marsh vegetation from the vegetation subroutine, erosion of back barrier marsh area via the morphology subroutine, and hydrodynamic exchange through tidal inlets from the hydrology subroutine.

Below are specific comparisons of the 2017 BIMODE and the 2012 barrier shoreline morphology model.

17.1 Model Language

The 2012 model was coded using Matlab ver. 2010. The 2017 BIMODE source code was written using Fortran 90. This change was selected by the modeling team to increase model speed and to facilitate merging it with the other subroutines of the ICM.

17.2 Wave Input and Transformation

The 2012 model effort used 20 years (1989 – 2009) of Wave Information Studies (WIS) data (Hubertz and Brooks, 1992). The WIS data was integrated into annual average data using wave height and direction bins (Hughes et al., 2012). This provided 20 sets of wave height and direction per WIS location to drive long-shore transport. The sequence was repeated 2.5 times to provide a 50-year wave series. Ten WIS locations were used to develop the wave climate; three on the east side of the Mississippi River and seven on the west side of the Mississippi River. The 2017 modeling effort used 32 years of WIS data (1980-2012) to develop wave statistics and input. The 2017 subroutine developed monthly average wave height, period, and direction data from the WIS dataset. This provided 384 different sets of wave height and direction per WIS location. Six WIS locations were used as inputs into the model; two on the east side of the Mississippi River and four on the west side of the Mississippi River.

The 2012 model used the wave angle at the WIS station and the shoreline angle to drive long-shore sediment transport and a simple shoaling algorithm was used to address changes in wave height. The 2017 modeling effort used the Simulating Waves Nearshore (SWAN) model to transform the waves from the WIS station to the – 4 m contour. This allowed for wave refraction, shoaling, breaking, damping, etc., from the offshore wave location to a location closer to shore.

The 2012 model effort smoothed the wave angle at each time-step (i.e., annually) when calculating long-shore transport. The extent of smoothing was based on the island width and shoreline length and used between one and three smoothing passes. The 2017 model smoothed the wave angle over 1,500 m and used a “staggered smooth” for profiles within 1,500 m of the end of a littoral cell. This involved using fewer profiles for the smoothing when within 1,500 m of the end of the littoral cell.

17.3 Cross-shore Response

The 2012 model did not include a cross-shore response due to tropical storm events. The 2017 version includes a cross-shore response by incorporating output from the Storm Induced Beach Change Model (SBEACH). The BIMODE subroutine selects the SBEACH profile that most closely resembles the BIMODE profile and applies the change between the input and output SBEACH profiles to the BIMODE profile. Thus, the lowering and overwash of the profile due to tropical storms is included in the 2017 model.

17.4 Shoreline Smoothing

The 2012 model smoothed the shoreline location across five adjacent profiles. A fixed cross-shore shape was assumed. The 2017 BIMODE code did not include shoreline smoothing because the shape of the cross-shore profile was revised using SBEACH.

17.5 Breaching

The 2012 model did not include criteria for the initiation of breaching. The 2017 subroutine includes several criteria for the development of breaches within an island chain including minimum island width, ratio of distance of the potential breach from the end of the island, and breach width-to-length ratio. Breaches are provided as feedback into the ICM as a way to capture hydrodynamic changes that may affect other subroutines.

17.6 Bay Feedback Frequency

Considering the timing for model feedbacks, the 2012 model only provided the cross-sectional area for an inlet every 25 years. The 2017 version of the model provides this on an annual basis.

17.7 Marsh Impacts

The 2012 barrier island model included a marsh accretion formula. For 2017, this is captured as part of the wetland morphology subroutine. The 2012 model did not include bayside marsh recession. A constant value – based on historic marsh recession rates – was included in the 2017 BIMODE subroutine for areas where the bayside marsh is exposed to wave action.

17.8 Calibration

The 2012 model was calibrated using shoreline changes between 1989 and 2009-2010. The 2017 model was calibrated using data from January 2006-December 2014.

18.0 Vegetation

The vegetation subroutine is a coast wide model integrated into the ICM and predicts changes in coastal vegetation types and coverage. It is directly linked to the hydrology and morphology subroutines. The update of the vegetation subroutine (LAVegMod 2.0) for the 2017 Coastal Master Plan builds on the strategy used in the 2012 Vegetation Model (LAVegMod) (Visser et al., 2013). The approach characterizes each species by the range of environmental conditions that promote or inhibit the growth of individuals per 500 m x 500 m grid cells. Dynamic changes in the species composition of the community arise as environmental conditions shift from favoring one species to favoring another. The change in vegetation at a site is driven first by mortality of existing vegetation due to the current environmental conditions. The mortality is interpreted by the model as a loss of species cover at a location. The reduction in plant cover caused by mortality creates space for the establishment of other wetland plant species. Unoccupied land also can occur as a result of soil morphodynamics and the creation of new land. Establishment of a species on unoccupied area is driven by the environmental conditions during the year in which the species establishes.

Significant changes have been made for LaVegMod 2.0. These changes fall into four broad categories. First, the number of habitats covered by the model has significantly increased. A number of species not included in the previous model have been added, and habitat types that represented aggregates of several species in the previous model have been divided into individual species for the revised model (Table 12). Second, the model code has been updated to reflect species-level niche requirements and ability to colonize a new cell. Third, the model has added the effects of dispersal on community dynamics. Finally, the model code has been streamlined and converted to the Python programming language for integration into the ICM. In addition, the similarity between the outputs from the two model versions was tested using one hydrology file from the 2012 Coastal Master Plan effort.

18.1 New Vegetation Habitats and Processes

The updated vegetation subroutine includes both an increase in the number of emergent wetland species as well as the inclusion of new species that represent new habitats (Table 12). New habitats included for 2017 include dunes and swales, bottomland hardwoods, and floating marshes.

Dune and swale communities occur along very sharp gradients that are primarily driven by elevation. To help capture these sharp gradients, the vegetation team attempted to apply polygons based on 5 cm elevation contours on the barrier islands rather than the 500 m x 500 m vegetation grid cells used in other habitats; however, due to large computing requirements of the vegetation subroutine, it was not feasible to implement a finer resolution along the barrier islands, and the 500 m x 500 m vegetation grid was used. Mortality and establishment probability matrices are based on unpublished data from Dr. Mark Hester (refer to Attachment C3-5 – Vegetation) and literature on the distribution of these species in dune and swale environments. The ecology of these species is different than that of the emergent marsh species. Mortality and establishment processes for dune and swale species are most strongly influenced by elevation above the water surface, as opposed to salinity and water depth variation for the emergent marsh species. Due to time constraints during the code development phase, the barrier island algorithm does not take dispersal or spread into consideration. As bare ground becomes available when species die, it is proportionally occupied by all barrier island species based on the elevation of the polygon in the year of establishment.

Bottomland hardwood species have also been included for 2017. The ecology of these species is also distinct from that of emergent marsh species, with distribution primarily driven by their elevation relative to mean water level. In addition, similar to swamp species, bottomland hardwood species can only establish from seeds that germinate in the spring and early summer under moist (not flooded) conditions and, once germinated, seedlings cannot survive when deeply flooded. Therefore, the algorithm for these species limits establishment to periods between March 1 and July 30 in which there are two weeks when water levels are below the soil surface, followed by two weeks of water levels not greater than 10 cm above the soil surface. The mortality and establishment processes for these species and the parameterization for the associated algorithms were generated by Dr. Gary Shaffer’s unpublished data (refer to Attachment C3-5 – Vegetation) for the bottomland hardwood species, as well as a review of the literature on the distribution of these species. New algorithms were added to the vegetation subroutine to reflect the distinct ecology of bottomland hardwoods.

Floating marshes occur in fresh water environments, and although numerous hypotheses regarding their ecology have been proposed, the exact mechanism for establishment of these marshes in Louisiana remains unclear. There is a quantity of information regarding the processes that lead to the demise of these habitats; therefore, the revised vegetation subroutine focuses on how these marshes are eliminated. Elimination of the floating marsh occurs when mortality of one of the floating marsh species occurs and is not replaced by the establishment of another floating marsh species. This leads to the death of the floating marsh and the conversion of the area vacated by these species to water. This information is then communicated to the ICM morphology subroutine.

18.2 Species Level Niche Requirements

Niche requirements for the emergent marsh and swamp forest species in the vegetation subroutine are based on at least 20 occurrences of the species in the Coastwide Reference Monitoring System (CRMS) data. The standard deviation of the daily mean stage (hereafter referred to as water level variability, or WLV) and average annual salinity were merged with vegetation cover data for each of the 392 CRMS sites using annual observations from 2006-2012. The weighted probability distribution – using percent cover as the weight – of the hydrology variables was then calculated for each of the species. For mortality, the center of the distribution of the species between the 25th and 75th percentile of both WLV and salinity was assigned 0% mortality. Outside of the 5th and 95th percentile of salinity, the mortality was set to 100%. Because the observed WLV is lower than the expected species tolerance, the mortality probability function was stretched so that the increase in mortality is slower as WLV increases. For establishment probabilities, the mortality matrices were inverted and shifted one model grid cell towards lower salinity and one cell towards either higher or lower WLV depending on if the species prefers lower or higher WLV. Establishment of species in a cell is determined by availability of space, the availability of species in the eight cells surrounding it, as well as those species that are in the cell, and is proportional based on the establishment probabilities of those species based on the hydrologic conditions in the year of establishment.

18.3 Dispersal

Dispersal is an important process governing the distribution of species on the landscape. The 2012 version of the code (LAVegMod) did not include the effects of dispersal, and when land became available for a species to establish either through mortality or land building, any species that matched the current environmental conditions could become established. This happened regardless of whether or not a species had representatives in the surrounding area to provide seeds or propagules. This may have resulted in unrealistic behavior in the first generation of the model. In the 2017 version (LAVegMod 2.0), algorithms that account for the ecology of plant dispersal have been incorporated. In the revised subroutine, plant species can only become established in a new area if the species is already present in the surrounding area or in the cell. Currently, the surrounding area is defined as the eight immediate 500 m x 500 m cells that surround a 500 m x 500 m cell. The result of adding dispersal is the prevention of species from appearing in unrealistic locations, as well as a more realistic pattern of species advance and retreat over the landscape as environmental conditions change.

18.4 Programming Language

In addition to revising and expanding the range of ecological phenomena captured by the model, a substantial effort has been undertaken to implement the model in Python. The previous version of LAVegMod used a combination of R and C++ code. Translation of the model into Python reduced the size (i.e., number of lines) of the code base, simplified many of the algorithms, made the subroutine easier to integrate with the overall ICM, and simplified the communication of information back and forth between ICM subroutines. Additional simplifications were also made where possible because of basic structural differences between Python and C++.

Table 12: Species and habitats included in LAVegMod 2.0.

LaVegMod Habitats	LaVegMod 2.0 Habitats	Continued Species	New Species
	Bottomland Hardwood Forest		*Quercus lyrata* Walter, *Quercus texana* Buckley *Quercus.laurifolia* Michx. *Ulmus americana* L., *Quercus nigra* L., *Quercus virginiana* Mill.
Swamp Forest	Swamp Forest	*Taxodium distichum* (L.) Rich *Nyssa aquatica* L. (these were represented together in the swamp category)	*Salix nigra* Marshall *Taxodium distichum* (L.) Rich *Nyssa aquatica* L. (each species is now represented individually)
	Fresh Floating Marsh		*Panicum hemitomon* Schult. *Eleocharis baldwinii* (Torr.) Chapm. *Hydrocotyle umbellata* L.

LaVegMod Habitats	**LaVegMod 2.0 Habitats**	**Continued Species**	**New Species**
Fresh Marsh	Fresh Attached Marsh	*Morella cerifera* (L.) Small *Panicum hemitomon* Schult. *Zizaniopsis miliacea* (Michx.) Döll & Asch. *Typha domingensis* Pers. *Sagittaria lancifolia L.*	*Sagittaria latifolia* Willd.
Intermediate Marsh	Intermediate Marsh	*Phragmites australis* (Cav.) Trin. ex Steud. *Schoenoplectus californicus* (C.A. Mey.) Palla	*Iva frutescens* L. *Baccharis halimifolia* L.
Brackish Marsh	Brackish Marsh	*Spartina patens* (Aiton) Muhl. *Paspalum vaginatum* Sw.	
Saline Marsh	Saline Marsh	*Juncus roemerianus* Scheele *Distichlis spicata* (L.) Greene *Spartina alterniflora* Loisel. *Avicennia germinans* (L.) L.	
	Dune		*Uniola paniculata* L. *Panicum amarum* Elliott *Sporobolus virginicus* (L.) Kunth.
	Swale		*Spartina patens* (Aiton) Muhl. *Distichlis spicata* (L.) Greene *Solidago sempervirens* L. *Strophostyles helvola* (L.) Elliott *Baccharis halimifolia* L.

19.0 Habitat Suitability Indices (HSIs) – Fish, Shellfish, and Wildlife

Habitat suitability index (HSI) models are used to generate a relative score for the condition (i.e., suitability) of an area to support a particular organism. HSI models consist of simplified relationships that relate key environmental variables to the quality of the habitat for that organism. The relationships, termed suitability indices, are standardized on a 0 to 1 scale, with 1 being the most favorable conditions and 0 being completely unsuitable. The relationships used to develop the suitability indices are often derived using literature or expert professional judgment. The suitability indices are then aggregated, often using an arithmetic or geometric mean to produce a single HSI score for the area of interest. During the aggregation procedure, variables may be weighted higher than others given their relative importance to the organism. Although HSI models are often criticized because they quantify habitat conditions, which may not directly correlate to species abundance, they remain a practical and tractable way to assess changes in habitat quality for various species.

The 2012 Coastal Master Plan utilized both existing and newly developed HSIs to evaluate potential project effects on alligator (Nyman, 2012a), crawfish (Romaire, 2012), gadwall (Leberg, 2012a), mottled duck (Leberg, 2012b), green-winged teal (Leberg, 2012c), muskrat (Nyman, 2012b), neotropical migrant birds (Leberg, 2012d), river otters (Nyman, 2012c), roseate spoonbills (Leberg, 2012e), largemouth bass (Kaller, 2012), eastern oyster (Soniat, 2012), brown shrimp (Baltz, 2012a), white shrimp (Baltz, 2012b), and spotted seatrout (Baltz, 2012c) habitat. The HSIs were reevaluated and improved for use in the 2017 modeling effort. This included reassessing the species to be modeled, the environmental variables to be included, data and information available to support the selection of variables, and the formulation of the suitability functions.

The species selected for inclusion in the 2017 Coastal Master Plan modeling effort include: mottled duck, green-winged teal, gadwall, wild-caught crawfish, alligator, brown pelican, blue crab (juvenile), brown shrimp (large and small), white shrimp (large and small), Gulf menhaden (adult and juvenile), bay anchovy (adult and juvenile), spotted sea trout (adult and juvenile), largemouth bass, and oysters. Considering there are no existing HSI models for brown pelican and blue crab, new HSIs were developed for this effort. An attempt was made to develop an HSI for blue catfish; however, this was not possible due to a lack of associated literature and/or supporting data. Similar to the 2012 effort, the 2017 HSIs are at a model grid cell resolution of 500 m x 500 m.

The HSI model improvement effort had three main focuses: (1) updates of HSI models for five wildlife species, i.e., three water fowl species (mottled duck, green-winged teal, and gadwall), wild-caught crawfish, and alligator, (2) development of new HSI models for brown pelican and blue crab, and (3) improvements of HSI models for the following fish and shellfish species: brown shrimp, white shrimp, Gulf menhaden, bay anchovy, speckled trout, largemouth bass, and oysters. The wildlife, fish, and shellfish HSI models were developed or improved upon by first identifying the life stages that should be represented in the models. Next, literature reviews were conducted to determine the key environmental variables that influence habitat quality for the selected life stages for each species of interest. For the wildlife species (i.e., waterfowl, crawfish, and alligator), outcomes of the literature reviews and expert professional judgment were used to update the existing equations or generate new suitability equations for each variable in the HSI models. For the fish and shellfish species, an additional step was taken to generate new suitability equations using existing field data from the Louisiana Department of Wildlife and Fisheries long-term fisheries-independent monitoring program. Statistical relationships were developed using the field data to predict fish and shellfish abundance (i.e., catch per unit effort [CPUE]) from key environmental variables collected concurrently with the fish sampling, namely salinity, temperature, and in some instances where it was considered an important determinant of abundance, turbidity. The newly developed statistical models were used with combinations of salinity, temperature, and turbidity (where applicable) within ranges found during the period of record in order to determine the maximum CPUE value for the model. The statistical models were then standardized to a 0 to 1 scale by the maximum CPUE value. For key environmental variables in which statistical relationships could not be developed, such as marsh habitat area and chlorophyll a, literature values and expert professional judgment were used to generate suitability indices. The final HSI equation for each species was then generated by aggregating all suitability indices – statistically and expertly derived – using the geometric or arithmetic mean.

The revised (or newly developed) fish and shellfish HSIs are an improvement over the traditional HSI approach, as it utilized independent fisheries data to develop statistically based relationships between species relative abundance and key environmental variables.

For additional information regarding the HSIs, refer to the individual species attachments:

- Attachment C3-6 – Gadwall Habitat Suitability Index Model
- Attachment C3-7 – Green-winged Teal Habitat Suitability Index Model
- Attachment C3-8 – Mottled Duck Habitat Suitability Index Model
- Attachment C3-9 – Brown Pelican Habitat Suitability Index Model
- Attachment C3-10 – Alligator Habitat Suitability Index Model
- Attachment C3-11 – Blue Crab Habitat Suitability Index Model
- Attachment C3-12 – Oyster Habitat Suitability Index Model
- Attachment C3-13 – Brown Shrimp Habitat Suitability Index Model
- Attachment C3-14 – White Shrimp Habitat Suitability Index Model
- Attachment C3-15 – Gulf Menhaden Habitat Suitability Index Model
- Attachment C3-16 – Spotted Seatrout Habitat Suitability Index Model
- Attachment C3-17 – Bay Anchovy Habitat Suitability Index Model
- Attachment C3-18 – Largemouth Bass Habitat Suitability Index Model
- Attachment C3-19 – Crayfish Habitat Suitability Index Model

20.0 Nitrogen Uptake

The potential for aquatic and estuarine ecosystems to mitigate increased loads of inorganic nitrogen (N) is perhaps nowhere more important than in the coastal region of Louisiana. Denitrification is a major pathway for the removal of inorganic nitrogen in lakes, rivers, and coastal estuaries. This reduction is biologically mediated through a series of intermediate products to gaseous nitrogen (N_2) representing a direct loss of nitrate to the atmosphere. As nitrate-enriched water masses flow through the landscape, the presence of riparian, headwater streams, and coastal wetlands can efficiently remove reactive nitrogen.

The model used in the 2012 Coastal Master Plan (Rivera-Monroy et al., 2013) was based on previous experimental studies and work performed during the Coastal Louisiana Ecosystem Assessment and Restoration (CLEAR) Program (Rivera-Monroy et al, 2003). It used the spatial statistical approach (SSA) to utilize denitrification datasets in several habitats in coastal Louisiana as well as current estimates of nitrogen loading rates for comparative analyses of different project effects. The 2017 Coastal Master Plan nitrogen uptake subroutine uses the same approach as 2012, with several updates as described below. The 2017 version is a subroutine of the ICM and uses information derived from various other subroutines to evaluate the potential fate of nitrogen (nitrate, NO_3) in different types of wetlands and open water bodies. Specifically, the nitrogen uptake subroutine uses outputs from the hydrology and vegetation subroutines.

The SSA model provides a first-rate estimation of inorganic nitrogen removal (NO_3) that can be used to assess how protection and restoration projects could affect nitrogen removal in wetlands surrounding areas influenced by management decisions. Nitrogen removal is estimated using in situ values of denitrification rates. The approach implemented in the 2017 subroutine uses classifications of vegetation type – at a cell resolution of 500 m x 500 m – and site-specific denitrification rates directly measured in coastal Louisiana. Hydrology, salinity, and temperature output from the hydrology subroutine drive output from the vegetation subroutine (i.e., spatial explicit type of wetlands including areal extension), and temperature is also used as a modifier in the calculations of denitrification. The subroutine separately estimates nitrogen removal for benthic sediments. The SSA estimates N removed in vegetated areas using information on vegetation distribution (500 m x 500 m), and adds the N removal from benthic sediment to calculate the total nitrogen (TN) removal value per coastal region. This is the final value provided by the SSA model. The total nitrogen removal obtained by the SSA represents the spatially explicit removal of nitrogen in different types of wetlands and benthic sediments, as these landscape categories change as a response to restoration actions.

For 2017, the same basic approach as that applied for the 2012 Coastal Master Plan was applied. However, as in situ values drive the rates applied in the model, an additional literature review was conducted to update the values based on the literature. The vegetation classification for which the denitrification rates are estimated was also updated to reflect the ability of the 2017 vegetation subroutine to resolve bottom land hardwood (BLH) and cypress-tupelo swamp vegetation types. For each land cover type, e.g., BLH, swamp, fresh/intermediate marsh, brackish marsh, saline marsh, and open water (with or without submerged aquatic vegetation [SAV]), a median denitrification rate was derived from the means found in the literature. This is the value applied in the subroutine, although the range of values from the available data is also reported should uncertainty analysis be conducted that can explore the sensitivity of model outputs to changes in the values.

For additional information regarding the 2017 nitrogen uptake subroutine, refer to Attachment C3-21 – Nitrogen Uptake.

21.0 ICM Conceptual Diagram and Narrative

As previously described, the dynamics incorporated in the 2012 Coastal Master Plan modeling effort combined with extensive improvements undertaken for the 2017 modeling effort resulted in an integrated process-based approach. The ICM represents many of the important processes driving coastal land and ecosystem change in the Louisiana coast. The interactions among the physical and vegetative processes included in the various subroutines are shown in Figure 13 along an idealized cross profile. The influence of changes in the physical environment and vegetation cover on water quality, habitat suitability, and fish and shellfish biomass is not currently represented in the conceptual diagram. This section is intended to provide an overview of all aspects of the ICM, including the linkages and interactions made possible through this new integrated approach to coding.

Within the ICM, temporal change is generally reflective of the temporal scale of direct measurements (e.g., 30 second frequency for hydrology, annual changes in shoreline position on barrier shorelines) and the temporal scale of the processes influencing change (e.g., growing season tolerance of vegetation to environmental conditions). Initialization conditions and forcing of the model for 50 year simulations is described in the hydrologic boundary conditions and landscape data sections below. As described in previous sections, a number of process interactions are represented only coarsely in the ICM due to lack of information or understanding, or because the ICM focuses on decadal scale coast wide change. In addition, the model development team was very aware that the purpose of the ICM is to evaluate the outcomes of an array of ecosystem restoration and protection projects both individually and in combinations. The focus was on including sufficient detail to accomplish that goal consistently across the coastal landscape.

Figure 13 shows forcing from the Gulf of Mexico in terms of tides and storms influencing water level, a Gulf salinity that is propagated into the estuary, and both tropical storm and non-storm waves that influence barrier island cross-shore and long-shore changes, respectively. Tropical storms occur throughout the 50-year ICM runs, reflecting the historical pattern of storm effects as modified by the future scenarios (Chapter 2). Sea level rise is imposed at the Gulf boundary, and the ICM propagates the effects on coastal hydrology. Many simple models of coastal wetland dynamics impose a system wide water level increase to reflect sea level rise (e.g., SLAMM; Warren Pinnacle Consulting, Inc., 2012). The ICM is not a 'bathtub' model; rather, it dynamically incorporates the effects of long-term progressive change in water level at the Gulf boundary. The ICM also has the ability to propagate elevated water levels (e.g., from tropical storms) though the hydrology compartments using a series of newly incorporated overland flow links.

On barrier shorelines, months that include tropical storm effects show a change in the cross profile caused by the event. Sand can overwash onto back barrier marshes changing elevation and potentially converting them to be dominated by swale vegetation. Depending on island shape at the time of the storm event, breaches can occur. Under non-storm conditions, Gulf waves result in long-shore movement of sediment, and island cross-shore profiles are modified monthly to show these effects. Thus, when a tropical storm impact occurs, adjustments are made based on the cross-shore profile that exists the month before the event occurs. Restoration projects change the cross-shore profile of the barrier islands/shoreline (i.e., the height, width and slope of components such as the beach, dune and back barrier marsh) and the ICM adjusts the profiles based on these profile shapes for all time periods following construction. At the end of each year, the resulting profiles are used to update the DEM and as the starting point for the following year.

At the inland margins of the ICM domain, rivers and existing flow diversions from the Mississippi River (e.g., Bonnet Carre spillway, Caernarvon, etc.) provide freshwater to the estuary (Figure 13). Freshwater is also supplied via rainfall, which is applied to all hydrology compartments consistent with the relevant future scenario. Upland streams, as well as the Mississippi and Atchafalaya Rivers also provide inputs of suspended sediment, nutrients, and other water quality parameters. Within the bays, as in the open water sections of all compartments, wind[5], waves and flow[6] re-suspend sediments from the mobile sediment pool on the bed. Four sediment components (sand, silt, clay and flocculants) are tracked. Sediments are also introduced into suspension as a result of an erosion term (calculated from historical rates) applied to wetland shorelines, including the back barrier marshes. Coast wide organic matter and bulk density values are assumed for all eroded 'edge' sediment and added as a source of total suspended sediment in the hydrology subroutine. The edge sediment load is much smaller than the other sediment sources, so this was included as a simplifying assumption. Organic matter and bulk density are varied, however, by vegetation type when converting the inorganic sediment load

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[5] The diagram does not explicitly show wind re-suspending; it shows wind influencing waves, which re-suspend.

[6] The diagram does not explicitly show flow.

on the marsh surface into a vertical accretion term in the morphology subroutine. In open water, flocculation varies with salinity, which is calculated for each hydrology compartment based on direct freshwater inputs (e.g., rain, tributary streams) and inputs from adjacent compartments. Settling velocities are calculated separately for each sediment class. Stage is tracked in all compartments and in those with a wetland component, suspended sediments are moved onto the marsh when the water level exceeds the height of the marsh surface. During periods of decreasing stage, water moves back into the open water but sediment does not (i.e., it remains on the marsh). Sediment is deposited on the marsh surface based on the depth and duration of flooding and the settling velocity of the different sediment size classes. During periods of high water depth on the marsh surface, flow of water, sediment, and other constituents can occur between adjacent marsh areas through overland flow links.

Vegetation cover is adjusted on an annual basis based on the elevation of the dune/swale above the mean water level on barrier islands, and the salinity and water level conditions for the wetlands. Forested wetland species are updated on the basis of water depth, and submerged aquatic vegetation (SAV) is updated on the basis of mean summer water depth, salinity and temperature. Thirty-two different species of vegetation are tracked and adjusted based on annual hydrologic conditions and the proximity of potentially colonizing species; dune and swale species are tracked on the basis of elevation above mean water level. Individual wetland species are grouped into five habitats (fresh forested, fresh, intermediate, brackish and saline marsh) that are used to assign organic matter characteristics to the wetland soils. The resulting organic matter percentage is used in combination with the annual amount of inorganic sediment deposited on the wetland surface to determine the annual accretion on the wetland surface. This is combined with subsidence to determine annual change in wetland elevation. At the end of each year, a determination is made on whether the wetland area is maintained. For fresh wetlands, the salinity during the preceding year is used to assess whether the salinity threshold is crossed. For all other wetland types, the threshold is based on the depth of flooding. Based on these calculations for the wetlands and the end of year barrier shoreline profiles, the configuration of land and water and its elevation is assessed at the end of each year and used to update the DEM. The revised coastal DEM is used to reinitialize the hydrology calculations for the following year (e.g., new extents/depths of open water, new wetland elevations).

Water quality changes in open water areas are calculated using transport and reactions, which affect both dissolved particulate forms. Outputs include: total Kjeldahl nitrogen, water temperature, nitrate + nitrite nitrogen, ammonium nitrogen, dissolved organic nitrogen, total phosphorus, soluble phosphorus, phytoplankton as chlorophyll a, and detritus. The ICM deposits sediment onto the bed, but does not predict the fate of constituents once deposited. The water column is assumed to be fully mixed and aerobic at all locations and times. Thus, there are no transfers of nutrients from the bed to the water column of the type that can occur when the water column is anoxic, or oxygen deprived. Formulations used in the model in addition to these source/sink terms include stoichiometric relations, photosynthesis rates, temperature dependencies, phosphorus partitioning, and ammonium preference.

Various characteristics of the open water (e.g., depth, salinity, and chlorophyll a) are used in combination with characteristics of the wetland and barrier island environments to determine habitat suitability for eight species of fish and shellfish and six species of wildlife. In this manner, the suitability of the coastal system for a variety of commercially and recreationally important species is tracked on an annual basis. Some of the suitability models for species depend on habitat for others (e.g., suitability for brown pelicans depends in part on suitability for gulf menhaden). If suitability for a species depends on aspects of the coastal system that are not adjusted within the ICM (e.g., distance to human activity/communities) these values remain constant throughout the 50-year ICM simulations. In addition, ICM-generated values for daily/monthly salinity, monthly water temperature, and annual wetland distribution are provided to the EwE subroutine and are used to estimate changes in relative biomass for different life stages of 21 species of fish and shellfish (EwE is described in a later section). Habitat suitability and relative biomass calculations do not feedback to the ICM calculations. Within EwE, biomass in a year is dependent in part on biomass from the previous year. Habitat suitability for each year is calculated independently.

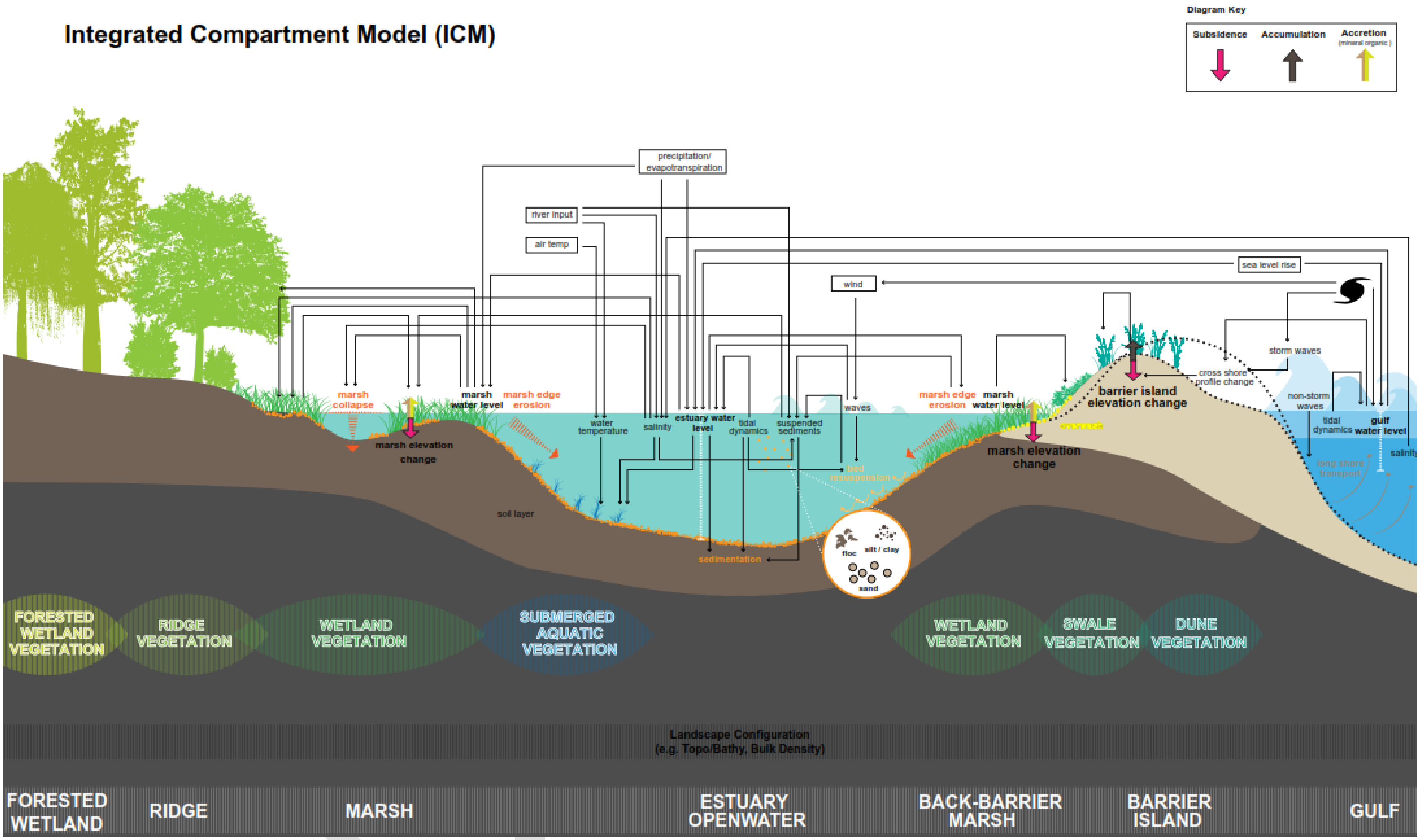

Figure 13: Conceptual overview of the processes represented in the Integrated Compartment Model (ICM).

22.0 Hydrology Boundary Conditions

Considering the effort to update the technical tools for the 2017 Coastal Master Plan, it was also critical to ensure that the most up-to-date data were used to drive calibration and validation of the newly developed ICM. As part of the task to improve input datasets and boundary conditions, a list of the data collection stations used in the 2012 Coastal Master Plan was assembled and newly available stations and sources of data to support improvements were added. The final list of data sources and stations was reviewed and approved by the broader modeling team.

Similar to the 2012 Coastal Master Plan, daily riverine inflow, hourly tidal stage, daily and discrete water quality, and daily precipitation and evapotranspiration data used to drive the ICM were collected from the following:

- U.S. Geological Survey (USGS)
- U.S. Army Corps of Engineers (USACE)
- National Oceanic and Atmospheric Administration (NOAA)
- National Oceanographic Data Center (NODC)
- Louisiana Department of Environmental Quality (LDEQ)
- Texas Commission on Environmental Quality (TCEQ)
- National Climatic Data Center (NCDC)

Missing data in the time-series were addressed using fitted relationships and linear interpolation where appropriate.

To inform the offshore stage boundary, water levels from four NOAA stations and one USGS station along the coast were used at the model offshore boundary. These stations, however, did not provide reliable datum conversions to the datum used by the ICM (i.e., North American Vertical Datum of 1988 Geiod12A [NAVD88 12A]) nor did they correct for subsidence and sea level rise. The USACE Southwest Pass gauge was used to convert to the NAVD88 Geoid12A datum and correct for subsidence and eustatic sea level rise. Additionally, further datum adjustments were made to minimize differences between the modeled stages and measured stages from CPRA's CRMS stations, which provided a consistent reference water level across the Louisiana coast near the Gulf of Mexico.

To obtain a better representation of the salinity in the offshore area, hourly salinity data from near-shore stations (as used in the 2012 Coastal Master Plan) were replaced with data from the NODC World Ocean Database (WOD). WOD is a database of Gulf measurements including salinity. These data were used to inform spatially varying, but temporally constant, salinity concentrations at the model offshore boundaries.

Wind data that was not originally used in the 2012 Coastal Master Plan were collected from the NCDC North American Regional Reanalysis (NARR) Model. The “reanalysis” incorporates observations from instruments and then assigns this output onto a regularly spaced grid of data (approximately 32 km x 32 km).

This documentation is specific to the boundary conditions used for ICM calibration and validation and the test model runs done to help identify future scenarios for use in production runs. For additional information regarding the hydrology related boundary condition data sets, refer to Attachment C3-26 – Hydrology and Water Quality Boundary Conditions. For additional information regarding how these datasets were altered to account for future scenarios in production runs, refer to Chapter 2 (Future Scenarios) and associated attachments.

23.0 Landscape Data

As described in the previous section, input data are one of the most influential determinants of model output quality. As such, an effort was undertaken to identify newly available or improved landscape specific input data to ensure the most up-to-date data were used to drive the 2017 Coastal Master Plan models.

Critical datasets for initializing the landscape components of the ICM were identified. These included: (1) a base period land and water composition dataset, (2) a base period integrated bathymetry and topography dataset, and (3) a dataset delineating the extent of vegetation community types. Each of these datasets constitutes a fundamental descriptor of the coastal landscape, and thus they affect most of the physical and biological processes that the master plan models simulate. Inaccuracies in these types of datasets manifest as inaccuracies in the models results, not only specific to the ICM, but also as it relates to the EwE fish and shellfish model and risk assessment modeling (described in later sections).

One of the most influential landscape datasets (i.e., land and water composition) is constantly changing in coastal Louisiana. Therefore, it was important to initialize models with the most up-to-date data to ensure that any land loss that has occurred since the 2012 Coastal Master Plan was accurately reflected in the base conditions of the new 2017 modeling effort. Similarly, any land gain, including the benefits from coastal restoration projects that have been completed since the last iteration of the plan, needed to be appropriately considered. For this reason, the latest available satellite imagery was compiled and analyzed to create a dataset that delineates the latest possible land and water composition of the coast.

Although land and water is a fundamental landscape descriptor, elevation is equally important when it comes to coastal modeling. The landscape composition dataset previously discussed outlines the horizontal aspect of the landscape, and the elevation data provide information on the vertical dimension. Elevation data are possibly the most critical landscape descriptor, but it is also a dataset with tremendous collection, processing, and accuracy challenges.

Finally, while the previous two datasets describe the three-dimensional landscape, the land cover classes, including the vegetation occupying that landscape, must also be described. Many coastal processes vary, depending upon the vegetation type occupying a site and as such, a dataset that describes the distribution of those classes is a necessary dataset for model initialization.

With these data priorities in mind, the 2017 Coastal Master Plan team undertook a rigorous effort to create datasets, which represent the best available data describing the landscape in coastal Louisiana. The data were collected from a multitude of sources, including satellite imagery and field data. While data collection dates vary, particularly with regard to elevation data, the datasets are intended to represent the late 2014 (November) time period. This served as the initialization time period for the 2017 Coastal Master Plan modeling effort. For additional information regarding the landscape datasets used in the ICM, refer to Attachment C3-27 – Landscape Data.

24.0 Tropical Storms in the ICM Boundary Conditions

Another improvement for the 2017 Coastal Master Plan modeling is the ability to capture effects of tropical storms (i.e., hurricanes and tropical storms) on the geomorphic evolution of the landscape. The ICM is driven with long-term records that include tropical storm-associated winds, precipitation, water levels, and waves. While a basic historic record of tropical storm occurrence is available for the Louisiana coast, the archive of historic data is not adequate to provide the level of detail required as input to the ICM. This section describes the approach used to identify approximations of tropical storms derived during a FEMA study of the Louisiana coast for use in the ICM boundary conditions. As part of the FEMA analysis, a suite of synthetic tropical storms was developed by USACE to represent probabilistic storm impacts along the Louisiana coast (USACE, 2008). The FEMA "storm suite" does not include very low-intensity events (i.e., central pressure > 975 mb), but the suite of synthetic storms does cover the range of hurricane-strength historical storms. Using the FEMA storm suite to approximate the historical 50-year tropical storm record compensates for sparse historical data and supplies consistent boundary conditions throughout the ICM domain for use in the landscape modeling.

As part of the 2012 Coastal Master Plan landscape modeling, the effects of tropical storms were included in only a few aspects of landscape dynamics. For instance, sediment deposition by storms in coastal marshes was assumed to occur at a constant annual average rate. Other effects, such as barrier island erosion and overwash could not be reflected in the analysis due to limitations in the modeling approach. Although these coastal dynamics are included in the 2017 Coastal Master Plan modeling, data for wind conditions, surge levels, and wave heights are available only at sparse gauge locations that do not coincide with the locations where data were needed for the ICM boundaries. Therefore, tropical storm boundary conditions for the ICM were derived from an existing set of synthetic hurricanes (developed for the abovementioned FEMA storm suite), for which detailed wind, surge, and wave model outputs were readily available at the spatial and temporal resolution required.

The HURDAT2 dataset was used to characterize historical storms that made landfall along the central, northern Gulf coast and generated significant surge and waves along coastal Louisiana. Each historical hurricane in the 50-year record (1963-2012) along the Louisiana coast was aligned with an individual storm in the synthetic storm suite, according to the approximate comparison of meteorological storm parameters. The alignment of storm events from the FEMA synthetic storm suite was completed by comparing storm track, central pressure, forward speed, and maximum wind speed. The composite of all identified synthetic events constitute an approximation of the historic hurricane record. While synthetic storm events do not exactly match all the details of their historical counterpart, the ICM is used to predict long-term trends for which the ensemble effects of all the storm events are more important than the accuracy of any discrete event in particular. Several options were developed to represent the historical pattern using the synthetic storms. Potential changes to the historical synthetic storm suite to represent changes in tropical storm intensity and frequency due to climate are addressed as part of 2017 Coastal Master Plan future scenarios (Chapter 2 and associated Attachments).

Tropical storm-induced precipitation data were also required by the ICM. Precipitation intensity and volumes for each representative synthetic storm event were calculated using the same empirical relationship used in the CLARA model as part of the 2012 Coastal Master Plan (Johnson et al, 2013).

The 2017 hydrology subroutine explicitly captures the effects of these events by applying elevated water levels (i.e., storm surge) at the offshore boundary and the storm's wind field temporally and spatially along the storm's path. For each event, sediment is delivered from the offshore compartments to the marsh as sediment is resuspended from the bed in open water due to higher wave energy, and the marsh is inundated due to higher water levels.

For additional information regarding the development of the 50-year historic tropical storm record, refer to Attachment C3-3 – Storms in the ICM Boundary Conditions.

25.0 ICM Calibration and Validation

As described in previous sections of this chapter, a number of technical advancements have been made for the models being used to inform the 2017 Coastal Master Plan. With continued advancements also comes the need to ensure thorough calibration and validation. This section provides an overview of the calibration and validation effort undertaken for the ICM subroutines.

Typically, key model parameters are identified by model developers and become the focus of calibration and validation efforts. Field or laboratory measurements are needed to serve as a "reference" against which model output is compared. The key model parameters are then fine-tuned until the model output compares well to the field/laboratory observations. Through the calibration process, a base or optimum value is established for each parameter of interest. Once this base value is established, no further changes to the key model parameters are allowed. At this point, and using these base values, additional model simulations are performed using an independent dataset that was not used in the calibration. This is called model validation. Both graphical and statistical metrics can be used to assess the model performance and how well it replicates the natural system being modeled. The understanding gained and the statistical evaluation of the level of agreement between the model output and field measurements is referred to as model performance assessment.

The ICM subroutines included in the calibration and validation effort are listed below, and the datasets and approaches used are provided in Table 13:

- Hydrodynamics
- Water quality
- Vegetation
- Morphology
- BIMODE (barrier islands)
- Habitat suitability indices (HSIs)

Unless otherwise noted in Table 13, the available record of field measurements that was deemed to be of acceptable quality and level of completeness and suitable to calibrate and validate the ICM was from 2006 – 2014. The period 2010 – 2014 was reserved for calibration while 2006 – 2009 was reserved for validation.

The modeling team reviewed model outputs and made adjustments to the model as needed until each model output was successfully calibrated (based on the approach/metrics in Table 13. For some model outputs, setting a quantitative metric was not possible; therefore, best professional judgment of a subject matter expert familiar with both the natural system and the model was the best approach to determine when the model had reached its optimal predictive ability.

For additional information regarding the calibration and validation effort for the ICM, including methods, analysis, and summary statistics, refer to Attachment C3-23 – ICM Calibration and Validation. EwE calibration is documented in Attachment C3-20 – Ecopath with Ecosim (EwE).

Table 13: Overview of the ICM calibration and validation effort.

Model Output	Data Used	Available Record	Approach/Metrics	Model Parameters to Adjust During Calibration
Stage	LDEQ, CRMS, USGS, NOAA	2006-2014	RMSE of 10-20%	• Cell/link dimensions • Observed tidal datum corrections • Hydraulic equations
Salinity	LDEQ, CRMS, USGS	2006-2014	RMSE of 20-30%	• Diffusivity
Flow	USGS	2006-2014	RMSE of 20-30%	• Cell/link dimensions • Observed tidal datum corrections • Hydraulic equations
Suspended Sediment	Long-term averages of grab TSS samples from USGS and LDEQ & reflectance imagery	varied	Best professional judgment based on long-term average TSS & spatial patterns identified from reflectivity imagery	• Resuspension coefficients
Sediment Accumulation	CRMS soil properties & measured accretion rates	varied	Best professional judgment based on marsh accumulation and mean suspended sediment concentration	• Resuspension coefficients • Marsh exchange flow
Nitrogen	LDEQ	2006-2014	Best professional judgment based on WQ grab sample datasets	• Sediment denitrification rate • Minimum nitrification rate
Algae	LDEQ	2006-2014	Best professional judgment based on WQ grab sample datasets	• Sediment denitrification rate • Salinity at which algal growth is halved • Phytoplankton mortality rate

Phosphorus	LDEQ	2006-2014	Best professional judgment based on WQ grab sample datasets	• Detritus dissolution rate • Phytoplankton respiration rate
Long-term (25-yr) accretion	Cesium cores (>100 cores)	2011-14 calib; 2006-10 valid	RMSE of 20% for mean annual accretion by region (PB, AA, CP) by wetland type	• Bulk density • Organic matter
Multi-year land area change rates	Historic land change rates from satellite imagery (Landsat)	2011-14 calib; 2006-10 valid	Within 10% of measured land change rates by ecoregion by wetland type	• Marsh collapse threshold • Only if needed: o Storm sediment distribution o Background land change rate o 2-zone sediment deposition
% cover per modeled vegetation species	CRMS vegetation data	2006-2014	Best professional judgment based on capturing stability or trajectories of change at 392 CRMS stations for all species	• Mortality and establishment tables for species for which the distributions are over or under estimated
Barrier island long-shore transport	BICM, LiDAR, historic reports	2003-2012	Best professional judgment based on accepted long-shore transport rates	• Long-shore transport coefficients (to obtain net long-shore transport rates that match sediment budgets presented in historic reports)
Barrier island cross- shore transport	BICM	2010	Best professional judgment based on overwash extent as calibrated for previous SBEACH efforts	• SBEACH transport rate coefficient • Slope dependent coefficient • Transport rate decay coefficient • Overwash
HSIs	n/a	n/a	Expert validation by reviewing outputs, associated input data, and determining if spatial pattern and magnitude was reasonable	

26.0 Ecopath with Ecosim (EwE)

A fish and shellfish community modeling approach was used in the 2017 Coastal Master Plan to evaluate effects of individual restoration and protection projects and alternatives (groups of projects) on fish and shellfish communities (hereafter referred to as fish) over fifty years under multiple environmental scenarios (i.e., multiple values of sea level rise, subsidence, etc.). To this purpose, a spatially explicit ecosystem model was developed in the Ecopath with Ecosim (EwE) software suite. The Fish and Shellfish Community Model simulates fish biomass distribution through time and space. This section describes the modeling approach, key assumptions of the model and modeling approach, and improvements made to fit the needs of the overall 2017 Coastal Master Plan modeling effort. The resulting Fish and Shellfish Community Model is described and examples of response curves and output are provided in this section. The methods planned to calibrate and validate the model, to provide a measure of model uncertainty, and to link the Ecospace model to the ICM are also provided.

26.1 Modeling Approach

A fish and shellfish community model that describes an extensive food web, represents predator-prey interactions, includes responses of fishes to environmental factors, and has the option of movement for nektonic species has the ability to simulate fish biomass and distribution in response to restoration and protection projects. In addition, it has become exceedingly clear that fishing is a very important determinant of fish and shellfish biomass in any ecosystem where fishing occurs (Worm et al., 2009) whether a species is targeted or a portion of the bycatch. Louisiana, known as the Sportsman's Paradise (Katner et al., 2001), and the state with the second highest commercial landings (by weight) in the United States (NOAA, 2014), is not an ecosystem where the effects of fishing can be disregarded. Ecopath with Ecosim (EwE) is a community modeling approach that can be used to simulate the combined effects of all of these ecosystem processes.

EwE is an open source ecosystem modeling software, originally developed by Polovina (1984) to model trophic interactions and to estimate mean annual biomass in a coral reef ecosystem. Since that time, the model has been greatly improved and is used to model ecosystems worldwide (Christensen and Pauly, 1992; Walters et al., 1997; Walters et al., 1999; Walters et al., 2000). The EwE modeling framework now consists of three modules: Ecopath, Ecosim, and Ecospace. The spatial application, Ecospace, was added in 1999 (Walters et al. 2000) and was included in a major recoding effort in 2006 to make the modeling suite more user-friendly, easier to adjust to individual modeling needs, and easier to link to other models. The EwE source code was migrated to the .NET programming environment, and this transition is one of the primary factors allowing for the development of a new and flexible spatial-temporal data framework in Ecospace.

All three modules have been used to develop the Fish and Shellfish Community Model. In short, Ecopath is a virtual representation of the food web of an ecosystem, including flows and pools of biomass within this food web. Ecosim then allows for temporal simulations of changes in biomass of groups in the model (which could be species or functional groups) in response to changes in water quality variables (such as nutrient loads and salinity) and fishing over time. Because of the trophic interactions represented in the initial food web, both direct and indirect effects of these drivers and forcing functions are made evident. Lastly, Ecospace allows for spatial and temporal simulations of biomass change of each of the groups in response to spatially and temporally explicit drivers, forcing functions, and habitat characteristics. This feature not only provides information on the spatial distribution of each group in the model, it also improves estimates of total biomass changes of each group over the course of the model run because movement of consumers, and spatially explicit habitat characteristics of the system are taken into consideration.

26.1.1 Ecopath

Ecopath is a mass-balanced ‘snapshot’ of the ecosystem. Species or groups in Ecopath can be divided into multiple life stages. This approach is referred to as the multistanza approach and can include a juvenile and adult for each group, or multiple life stages per group when ontogenetic shifts occur at several instances in the life cycle. The model is mass-balanced over a set time period; for the Fish and Shellfish Community Model this period is 1 year, which is most commonly used in EwE models (Christensen et al. 2008). The assumption of mass-balance implies that the flow of biomass into the model must equal the flow of biomass out of the model over the period of a year. Mass-balance occurs within the model when two governing equations are satisfied. The first equation describes the production term and can be expressed as:

$$B_i \cdot (P/B)_i \cdot EE_i - \sum_{i=1}^{n} B_j \cdot (Q/B)_j \cdot DC_{ji} - Y_i - E_i - BA_i = 0 \qquad (1)$$

Where: B_i and B_j are the biomasses of the prey (i) and predators (j) respectively; $(P/B)i$ the production/biomass ratio; EEi the ecotrophic efficiency, which is the proportion of the production that is utilized in the system; $(Q/B)j$ the consumption/biomass ratio; $DCji$ the fraction of prey (i) in the diet of predator (j); Y_i the total fishery catch rate of (i); Ei the net migration rate (emigration-immigration); and BA_i the biomass accumulation rate for (i). The second master equation ensures energy balance within each group as follows:

Consumption = production + respiration + unassimilated food (2)

To develop the Ecopath model, a proportional diet and at least three of the following parameters: initial biomass, production/biomass ratio, consumption/biomass ratio, and ecotrophic efficiency must be provided for each species or group. Using the master equations, the model will solve for the parameters that were not provided. After iterative tuning and calibration, a mass-balanced Ecopath model can be achieved. The resulting balanced model provides output that can be used to investigate food web dynamics, ecosystem networks, keystoneness, mean trophic level indices, among many others. It also provides a base model to use in temporal dynamic simulations in Ecosim, or temporal and spatial dynamic simulations in Ecospace.

26.1.2 Ecosim

Applying the initial parameters derived from the first master equation in Ecopath, the Ecosim module of EwE can be invoked. Ecosim re-expresses the system of linear equations from Ecopath as a system of coupled differential equations to predict future outcomes. Environmental factors can influence trophic interactions when included as forcing functions, which are used to alter the effective search rate of predators in a way determined by species-specific response curves. The effective search rate in Ecosim allows predators to spend more (or less) time foraging in arenas where prey are concentrated. To include forcing functions in the model, a dataset with monthly values of the environmental variables of interest is uploaded to the model. In addition, response curves are created that represent the tolerance ranges of each group in the model for the specific environmental variable.

26.1.3 Ecospace

Ecospace is the spatially explicit and time dynamic module of the EwE software package. In this module, the same set of differential equations applied in Ecosim is now applied in every grid cell over a geo-referenced base map (Christensen et al., 2004; Walters et al., 1997). Consumption rates are based on the Foraging Arena Theory (Walters and Martell, 2004), as is the case in Ecosim, allowing Ecospace to represent biomass and consumption dynamics over two-dimensional space (Christensen et al., 2008; Walters et al., 1999). While Ecosim runs in each Ecospace grid cell, a portion of the biomass of each group will move to adjacent grid cells in search of better living conditions with movement rate m in km yr^{-1}. Movement rate (m) can be user defined, and is set at a default of 300 km yr^{-1} when no specific swim speed is known for a specific group.

Groups in Ecospace respond to environmental drivers and habitat features following the Habitat Capacity Model (Christensen et al., 2014). External data or model output of environmental variables (salinity, temperature etc.), coupled to response curves that describe how groups respond to these drivers, are used to compute the suitability or Habitat Capacity (C) in a grid cell per time step. C is a unitless value between 0 (unsuitable) and 1 (maximum suitability); low C reduces consumption by reducing the size of the foraging arena area in a grid cell. In addition, movement is affected such that movement (of a specific group) towards unsuitable habitat in a neighboring cell is slowed as a function of C.

Fishing fleets (which can represent recreational fishing as well) are included and dynamic in Ecospace. Ecospace takes the Ecosim time series of fishing effort and distributes the effort across the map based on the biomass in a cell. Fishing mortality rates (F) are initially distributed between fleets based on the distribution in the underlying Ecopath base model. During an Ecospace run, F's are distributed over cells using a gravity model; the proportion of effort allocated to any particular cell is assumed proportional to the sum over groups of the product of the biomass of the target species and profitability of fishing in that particular cell (Christensen et al. 2008). Profitability is not calculated in the Fish and Shellfish Community Model and is directly related to biomass (making the gravity model solely respond to the biomass of target groups in a cell).

26.2 Improvements to the 2017 Coastal Master Plan

Several specific improvements to the EwE software and approach were made to accommodate the needs of the 2017 Coastal Master Plan. These can be summarized as follows:

- **Monthly time series** - Up to the most recent release of the EwE software, the 'fitting to time series' procedure used during calibration could only be achieved at an annual resolution. The software has now been modified to incorporate either monthly or annual biomass time series data.
- **Geospatial projection of model area** - The Ecospace module of the EwE software applies the ecological dynamics of a marine food web across a grid of cells. Traditionally, this grid is geo-referenced to decimal degrees longitude [-180, 180] and latitude [-90, 90], where cells taper at higher latitude ranges – the common WGS84 or EPSG:4326

projection. Ecospace automatically takes this projection into account in its functional groups dispersal calculations. For the 2017 Coastal Master Plan Fish and Shellfish Community Model, these calculations needed to be modified to enable habitat feature data input to Ecospace to be mapped to a local UTM spatial projection with highest positional accuracy.

- **Excluding map cells** - Historically, users could only exclude Ecospace map cells from computations by turning these cells to land. This would yield confusing maps with unrecognizable land contours. In response, the concept of excluded cells was introduced to the Ecospace model. These excluded cells do not contain ecosystem dynamics, are not considered in the Ecospace computations, and are not rendered in the map displays. In addition, a feature is added to explicitly display which cells were excluded on output maps.
- **Sharing external spatial datasets between computers** - The Ecospace module of the EwE software recently gained capabilities to be driven by external spatial-temporal datasets, a feature that is extensively used for the 2017 Coastal Master Plan Fish and Shellfish Community Model. These external data sets cannot be embedded within an EwE model because they tend to be model-derived datasets that frequently update and are of prohibitive file size. The process of connecting to these data is detailed in Steenbeek et al. (2013). Since the 2017 Coastal Master Plan Fish and Shellfish Community Modeling exercise would be executed by scientists of different institutes in different locations, this system needed to be extended to offer support for shared use of the same model with accompanying external spatial data via cloud-based transfer media.
- **Adding new ways to shape response curves** - The Ecosim and Ecospace modules contain forcing functions and mediation functions through which temporal and spatial dynamics of the model can be influenced. The predefined mathematical distributions already available in EwE did not contain shoulder and trapezoid distributions that would be needed for the 2017 Coastal Master Plan Fish and Shellfish Community Model. The EwE software now offers ten different distributions in addition to the ability to sketch in curves. The trapezoid distribution is extensively used in the Ecospace model developed to support the 2017 Coastal Master Plan.

26.3 Fish and Shellfish Community Model Description

The Fish and Shellfish Community Model represents 55 groups, 41 of which represent a life stage of a species and fourteen represent species aggregates (e.g., zooplankton; Table 14). The model was (initially) calibrated in Ecosim with 10 years of environmental parameter output derived from models supporting the 2012 Coastal Master Plan and biological field data collected during 2000-2009. The spatial grid for the Fish and Shellfish Community Model l was developed with a 1 km x 1 km resolution that represents coastal Louisiana (Figure 14). Environmental drivers in the model are salinity, temperature, Total Kjeldahl Nitrogen, total suspended solids, percent wetland, percent upland, depth, and percent cultch. Species respond to monthly values of each of these drivers with species-specific response curves (Figure 15). Suboptimal conditions for a specific species reduce its foraging arena area in an Ecospace grid cell following the Habitat Capacity Model (Christensen et al. 2014).

Table 14: Listing of all groups in the Fish and Shellfish Community Model.

Group name	Group name	Group name
juvenile Atlantic croaker	juvenile gulf sturgeon	Juvenile sheepshead
adult Atlantic croaker	adult gulf sturgeon	adult sheepshead
juvenile bay anchovy	killifishes	silversides
adult bay anchovy	juvenile largemouth bass	juvenile southern flounder
benthic algae	adult largemouth bass	adult flounder
benthic crustaceans	mollusks	juvenile spot
juvenile black drum	oyster drill	adult spot
adult black drum	oyster (spat)	juvenile spotted seatrout
juvenile blue catfish	oyster (seed)	adult spotted seatrout
adult blue catfish	oyster (sack)	juvenile striped mullet
juvenile blue crab	phytoplankton	adult striped mullet
adult blue crab	juvenile red drum	juvenile sunfishes
juvenile brown shrimp	adult red drum	adult sunfishes
adult brown shrimp	SAV	juvenile white shrimp
detritus	sea birds	adult white shrimp
dolphins	juvenile sea catfish	zoobenthos
grass shrimp	adult sea catfish	zooplankton
juvenile menhaden	juvenile sharks	
adult gulf menhaden	adult sharks	

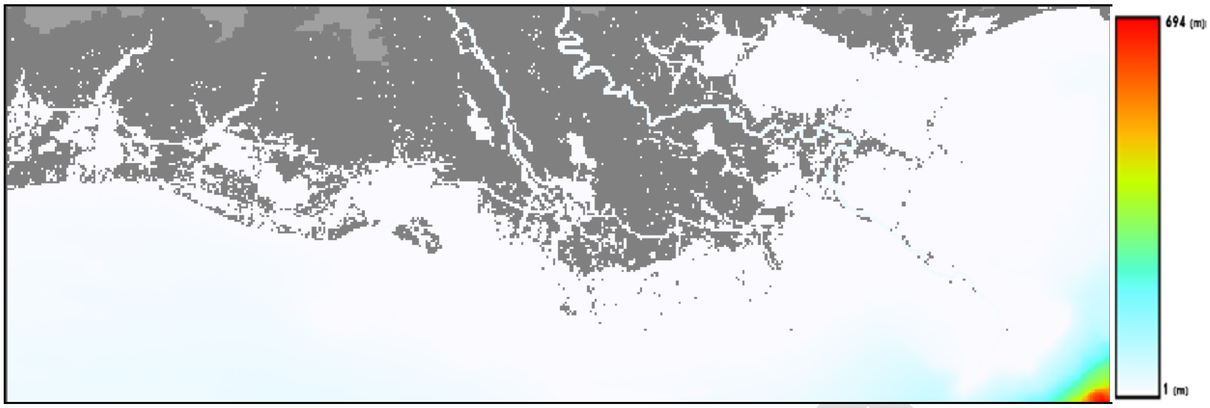

Figure 14: Model area of the coast wide Fish and Shellfish Community Model. While grey cell are inactive fish have access to all other areas, which include open water as well as wetlands, depending on their habitat preferences. Warmer colors in the active cells indicate increasing depth.

Since EwE has a monthly timestep, the model may miss short-term (< 1 month) unsuitable conditions that could have an effect on long-term biomass. As it was determined that this could pose an issue for oyster biomass estimates, Oyster Environmental Capacity Layers (OECLs) that can be read into Ecospace were developed. OECLs determine habitat capacity per month based on daily values of salinity, temperature, and TSS. The OECLs are then read into Ecospace in the same manner as the other environmental drivers.

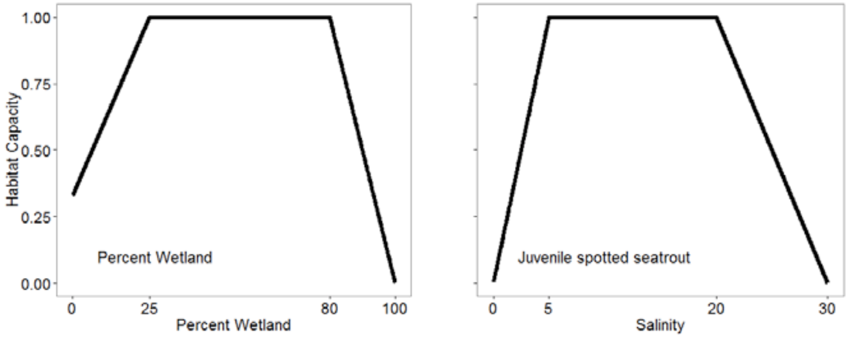

Figure 15: Examples of response curves. The first curve is applied to several species (mostly at the juvenile life stage) that are associated with wetlands. The second curve is one of the species-specific response curves to salinity and represents the response of juvenile spotted seatrout to salinity.

The output of an initial Ecospace model built for three basins in coastal Louisiana (i.e., Barataria Bay, Breton Sound, and Lake Pontchartrain) reflects fish biomass and fishery landings trends seen during the 2000-2009 time period. Twenty and 50-year simulations (2009-2059) have demonstrated that the Ecospace model remains stable while running over such long time periods. Preliminary example results of a group low in the food web (phytoplankton) and a group high in the food web (adult red drum) are shown in Figure 16 and Figure 17. These results highlight the ability of the model to provide output on decadal time scales, to incorporate fish response to environmental parameters, and to reproduce observed biomass.

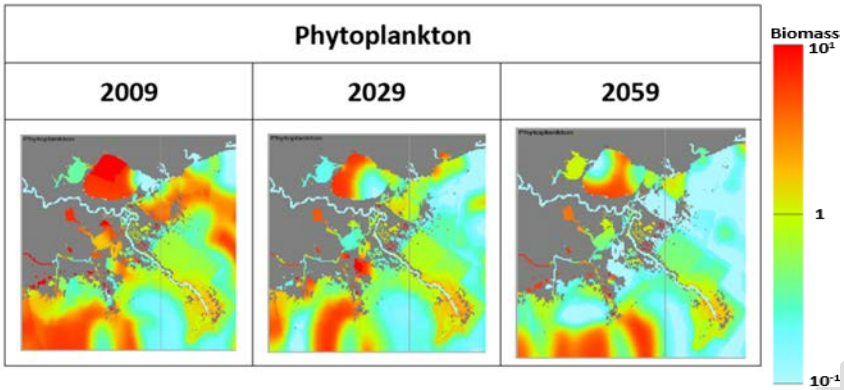

Figure 16: Ecospace model output for phytoplankton. The scale bar in the legend represents relative biomass on a log scale compared to initial biomass of this group.

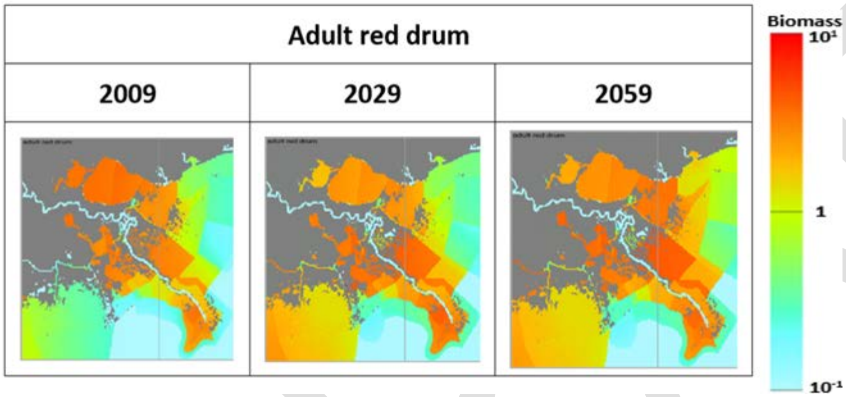

Figure 17: Ecospace model output for adult red drum. The scale bar in the legend represents relative biomass on a log scale compared to initial biomass of this group.

26.3.1 Key Model Assumptions

- The model mass balances over a period of a year.
- The species included in the model together provide a good representation of the food web in Louisiana estuaries.
- The diet of each group consists of species/groups present in the model, and diet switching does not occur.
- Including changes in environmental parameters at a monthly time step will realistically reflect effects of a changing environment on fish (except oyster; see next bullet-point).
- Including changes in salinity, temperature and TSS at a daily time step will realistically reflect effects of changes in environmental parameters on oysters.
- Movement of fish in the Ecospace model is only affected by the suitability of the environment determined by environmental parameters, habitat features, and levels of predation and fishing. Seasonal migration patterns are therefore not reflected in the model, as these movements do not stem from movement away from unsuitable conditions.

- Fleets included are representative of fishing in Louisiana.
- Fishing effort remains constant over the simulation time.

26.3.2 Model Tuning and Testing

Model calibration in EwE was carried out in the Ecosim module. During model calibration, biomass and landings output of groups in the model are fitted to observed biomass data and landings data for each group for which data are available. Model fitting in Ecosim is accomplished by having the model estimate the 'vulnerability of a group to predation' (v_{ij}) term that produces a better fit to the observed data. During the Fit to Time Series procedure, the model is iteratively fit to observed values with a new set of v_{ij}, and the sum of squared deviations (SS) of the observed logarithmic (log) biomass values is used to determine if these changes in allow the model to better recreate historical patterns of biomass (Christensen et al., 2008). The SS calculation used within Ecosim during the fitting process where Ecosim tests all combinations of v_{ij} values is as follows:

$$SS = \sum_i^{nts}\left(\sum_t^{nobs_i} w_i \log(o_{it}/p_{it})^2\right) \qquad (3)$$

Where: nts is the number of time series loaded; $nobs_i$ the number of observations in time series i,;w_i is the weight of the time series i; o_{it} is the observed value in time series i at time step t and p_{it} is the Ecosim predicted value for variable i at time step t.

The procedure stops fitting the model with new values to the observed data when no lower SS value is found by adjusting v_{ij}. These values acquired in Ecosim are then transferred to Ecospace. To provide goodness of fit measures that are comparable to other models, the root mean square error (RMSE) is used to assess the fit of predicted to observed as well. Further fine-tuning occurs by running the model in Ecospace, checking biomass and biomass distributions of each run, and changing input parameters manually within the range of reported values to produce realistic biomass and biomass distributions.

A sensitivity analysis was conducted in Ecosim using Monte Carlo simulations. This feature was used to vary the initial biomass of all groups in the model with a coefficient of variation (CV) of 0.1 over 20 model runs. The small CV was chosen to reveal whether small changes in initial biomass result in large changes in output biomass. This tests the robustness of the model, and also gives insight as to what the effects could be of changing certain parameters during the fine-tuning process. By having the biomass of all species vary at the same time, the potential impact of the changed biomasses of other species in the model through trophic interactions are tested with these Monte Carlo trials as well.

To spatially validate the model, the coast was first subdivided into ecoregions. Subsequently, per-region model output is compared to field collections from the corresponding ecoregion, and goodness-of-fit (i.e., RMSE) calculated. This method tests the quality of biomass predictions and spatial distribution. Using information on goodness of fit of the model to field collections calculated during model validation, confidence intervals can be created per ecoregion, per species that serve as an indication of model uncertainty.

26.4 Linking ICM to EwE

The 2017 Coastal Master Plan modeling effort aims to simulate a large number of projects under multiple environmental scenarios. The Fish and Shellfish Community model uses output of salinity, temperature, Total Kjeldahl Nitrogen, total suspended solids, and any changes in wetland coverage and habitat features from the ICM to drive changes in fish biomass and distribution. Due to the number of model runs needed for the 2017 effort (e.g., hundreds), it was necessary to automate data transfer from the ICM to the Fish and Shellfish Community model. The process by which model linking occurs between EwE and the ICM is described below.

26.4.1 Habitat Capacity Model

The Habitat Capacity Model offers the ability to drive foraging capacity for a species based on the cumulative impacts of physical and/or environmental factors such as depth, salinity and temperature. The Ecospace Spatial Temporal Framework is capable of loading GIS files that are used as spatial-temporal forcing data to drive changes over space and time to the inputs of the Habitat Capacity Model.

26.4.2 EwE Console App

To facilitate the linking of EwE to the ICM, a console version of EwE was developed that allows EwE to be configured and run from a text command line file. This version of EwE contains all the core computational functionality without the Scientific Interface. This allows multiple instances of EwE to be run at the same time from different inputs, with outputs from each instance of EwE being sent to different output directories. The command line file contains all the required configuration information for the Ecospace Spatial Temporal framework to load physical or environmental GIS input files that are used to drive changes in the Habitat Capacity Model.

26.4.3 ICM

The ICM joins models into a chain using the outputs from one model as the input to another. The console version of EwE is added to this chain by formatting the outputs from various models in the ICM into GIS input files that are read in via the Ecospace Spatial Temporal Framework. Once the file format conversion is done a new EwE text command line file is written and EwE is run on the new input data.

For additional information on the EwE model used for the 2017 Coastal Master Plan, refer to Attachment C3-20 – Ecopath with Ecosim (EwE).

27.0 Storm Surge and Wave Model Overview

The goal of the storm surge and waves model used in the 2017 Coastal Master Plan is to evaluate various coastal restoration and protection projects and the associated benefits with regards to storm surge and wave height reduction. Storm surge and wave climate responses for initial conditions and each future condition and project action were simulated using the coupled ADvanced CIRCulation (ADCIRC) and unstructured Simulating WAves Nearshore (UnSWAN) model system. Both models use an unstructured mesh, which allows for variation of model resolution from coarse in the open ocean to very fine near islands, channels, levees, and other areas where flow and wave radiation stress gradients are large. The unstructured mesh developed for the master plan allows for a precise representation of the topographic and bathymetric features and accurate representation of the flow conditions.

27.1 Comparisons between 2012 and 2017

In order to save on computational costs for the 2012 Coastal Master Plan, the inland extents of the master plan storm surge and waves model were defined by the extents of output locations required for the risk assessment model (Johnson et al., 2013). Beyond the output locations, external weir boundaries were applied in order to minimize computational overhead associated with areas not flooded by storm surge. To additionally reduce the computational overhead, interior reaches of polders were removed from the model as well. For instance, the New Orleans polder areas, which are surrounded by levee protection systems on all sides, are not included in the model simulation. Flood depths in polder areas are accounted for directly by the risk assessment model via the estimation of overtopping volumes using the storm surge and waves model output on the unprotected side of the polder (Johnson et al., 2013).

As part of the 2017 Coastal Master Plan, the 2012 models were updated to improve the representation of storm surge across Louisiana while maintaining the mission of providing a high-speed, physics-based modeling approach. The model geometry was updated in three critical ways: expansion of the inland extents, additional model resolution in select areas to enhance model skill, and inclusion of protected areas like the New Orleans polder areas. Polders were added to the storm surge and waves model to improve accuracy on the unprotected side and for quality review purposes. Figure 18 shows the changes in the model domain between 2012 and 2017 model versions with updated protected areas highlighted.

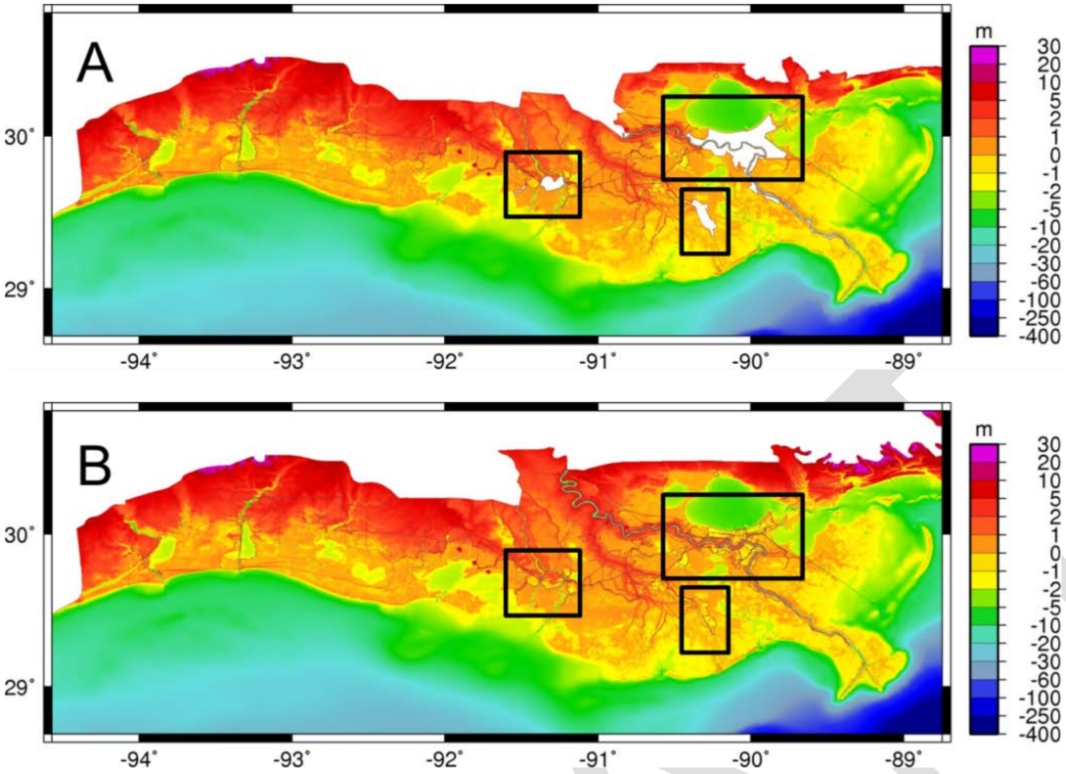

Figure 18: The (A) 2012 and (B) 2017 model elevations and updated polders. Warmer colors indicate higher elevations. Black boxes identify areas of model improvement within polders for the 2017 analysis improvements.

The critical ADCIRC and UnSWAN model inputs are elevation data at each node, surface roughness characteristics (e.g., bed roughness friction and land surface directional effective roughness length), initial and boundary conditions and system driving forces (inflows at the Mississippi and Atchafalaya Rivers, hurricane wind fields, hurricane pressure fields and tides at the open ocean boundaries).

Bathymetry and topography influences propagation and attenuation of wind-waves and surges. In the 2012 Coastal Master Plan, topography and bathymetry data applied to the model were the digital elevation model (DEM) output from the wetland and barrier shoreline morphology models (Couvillion et al., 2013; Hughes et al., 2012) for initial and future conditions. Accurate mapping of the elevation at each computational node is essential to correctly simulate inland flood propagation. Unique treatment of bathymetry, topography and pronounced vertical features (e.g., levees and highways) is critical to accurate elevation mapping. The 30-meter resolution DEM output was interpolated onto nodes applying a mesh scale averaging technique, which applies the area-weighted average according to the adjacent elemental resolution. For the development of the initial conditions mesh in the 2012 analysis, bathymetry and pronounced vertical features were mapped onto the mesh directly from previous ADCIRC model meshes developed in Louisiana by leading experts (USACE, 2008a-c) and updated based upon additional site specific survey data. For future conditions, elevations for all areas in the model, including bathymetry and pronounced vertical features, were updated based on outputs from the wetland and barrier shoreline morphology model to account for land subsidence and accretion. Additionally, future conditions design elevations for features such as levees were accounted for where necessary. Since the 2012 analysis, the 2017 initial conditions model elevations have been updated where new topography and bathymetry data were available. The same interpolation schemes and application methodologies were applied as the 2012 analysis. Model elevations for future conditions in the 2017 analysis will be provided by the ICM.

Surface roughness characteristics are critical nodal attributes as they are required for estimates of the wind energy input at the air-sea interface and energy dissipation at the seabed. In the case of water flowing or waves propagating over a surface, the bottom friction force is quantified using the Manning's *n* coefficient and the widely-used Manning's hydraulic equation. ADCIRC is able to convert Manning's *n* to a roughness length for the UnSWAN model's Madsen friction formulation. In the case of air flowing over land or water, directionally varying roughness lengths (Z_0) determined by the FEMA hazard loss estimation methodology program are used to adjust the wind boundary layer (FEMA, 2005). Both the Manning's *n* and Z_0 are relatively small coefficient values and generally constant over the water regions, with the exception of upwind effects associated with Z_0. Variations exist in the overland region, where land cover conditions vary from urbanization to agriculture, forests, swamps and marshes, as categorized in the Land Use and Land Cover (LULC) dataset by the U.S. Geological Survey. For the 2012 analysis, the LULC data were used outside of wetland areas to assign the surface roughness, while wetland morphology model land/water data (Couvillion et al., 2013) and vegetation model data (Visser et al., 2013) were applied in coastal wetland and open water areas. The mesh scale average technique applied for elevation mapping was employed to characterize the surface roughness characteristics at each node. The designation of Manning's *n* and Z_0 values for each class of land cover was guided by previous studies (Arcement and Schneider, 1989; Dietrich et al., 2011; USACE, 2008a-c). The 2017 model application will use the same surface characteristics. Though the characteristics will be updated for future conditions analyses based on ICM outputs rather than outputs from individual wetland morphology and vegetation models. Additionally, if updated LULC data are available, the initial conditions mapping will be revised.

The model initial conditions include a mean sea level adjustment, which is attributed to datum conversion, seasonal sea level fluctuation, and eustatic sea level rise for future conditions. Model boundary conditions include riverine inflows for the Atchafalaya and Mississippi Rivers and internal/external flow boundary conditions such as weir boundaries for levee systems. Tides are included in the model simulations of historic events for model validation; however, tides were not included in the simulation of synthetic storms and are instead accounted for as part of the risk assessment model inundation hazard assessment (Johnson et al., 2013).

Winds and pressure fields are the major atmospheric forcing in the hurricane system. A synthetic set of 446 storms was created in 2006 for the Joint Surge Study to estimate representative return storm events (USACE 2008a-c). The atmospheric forcing was generated utilizing the Planetary Boundary Layer model (Thompson and Cardone, 1996). For the 2012 Coastal Master Plan, 40 of the 446 production wind fields were simulated for each environmental condition and project analysis. Further details for storm selection as part of the 2012 analysis are described as part of the risk assessment model (Johnson et al., 2013). During the 2017 model improvement period, all 446 storms were simulated on the updated ADCIRC model domain shown in Figure 18. The ADCIRC and UnSWAN model outputs are currently being used to update the selection of production wind fields to be applied as part of the 2017 analysis.

Prior to the production storm simulations for initial and future conditions, the 2012 ADCIRC and UnSWAN models were validated under the initial condition by simulating Hurricanes Gustav and Ike, both making landfall in 2008. These two hurricanes were selected as test cases due to their relatively recent landfall dates, the availability of data assimilated wind and pressure fields and the extensive measurement data available throughout the state. Following the 2017 model improvements and prior to running the 446 storms state wide, the model was validated by simulating Hurricanes Gustav and Ike, as well as Hurricanes Katrina and Rita, both making landfall in 2005.

27.2 Storm Surge and Waves Model Interaction with the ICM and CLARA

As described by Peyronnin et al. (2013), for the 2012 Coastal Master Plan modeling effort, the storm surge and waves model required output directly from the wetland and barrier shoreline morphology models (Couvillion et al., 2013; Hughes et al., 2012) to determine landscape configuration and output from the vegetation model (Visser et al., 2013) to set roughness parameters. For the 2017 Coastal Master Plan, similar outputs will be provided from the ICM. Additionally, the storm surge and waves model provided flood stage time series, maximum wave height, and peak wave period data for use by the risk assessment model (Johnson et al., 2013) in the 2012 analysis and will do the same in 2017. The outputs were applied in the 2012 Coastal Master Plan and will be applied in the 2017 Coastal Master Plan to compute statistical inundation hazard by the risk assessment model at multiple year return periods (e.g., 50-, 100- and 500-year).

Storm surge and wave analyses in the 2012 Coastal Master Plan were completed for with and without action future conditions under three environmental scenarios at year 50: Moderate, Moderate with High Sea Level Rise, and Less Optimistic as described by Peyronnin et al. (2013). For the 2017 analysis, environmental scenarios, as well as multiple time periods including initial conditions, model year 50, and intermediate years, will be analyzed using the storm surge and waves model.

An interaction in the 2017 modeling paradigm that was present during the 2012 Coastal Master Plan is the use of storm surge and waves model data to drive the ICM. Stillwater elevation and wave characteristic model outputs for many of the 446 synthetic storms have been incorporated into the ICM (hydrology and barrier island subroutines) as part of the boundary conditions to define tropical storm event conditions as part of the various environmental scenarios that will be simulated.

For additional information on the storm surge and wave modeling refer to Attachment C3-25 – Storm Surge and Risk Assessment.

28.0 Coastal Louisiana Risk Assessment (CLARA) Model

The Coastal Louisiana Risk Assessment (CLARA) model is a quantitative simulation model of storm surge flood risk developed by a team of researchers at the RAND Corporation for use in the 2012 Coastal Master Plan. The purpose of CLARA was to better understand how future coastal changes could lead to increased risk from storm surge flooding to residents and assets on the Louisiana coast and assess the degree to which proposed projects could reduce this risk. CLARA allowed CPRA to systematically evaluate potential projects for inclusion in the 2012 Coastal Master Plan by estimating their risk reduction benefits. The methods and data used in CLARA, as well as the analysis conducted to support master plan development, are well-described in previously published literature (Fischbach, 2010; Fischbach et al., 2012; Johnson et al., 2013).

This section summarizes a number of improvements made to the CLARA model to support the 2017 Coastal Master Plan. The summary below is adapted from a more complete technical report, Fischbach et al. (2015), which describes in detail the model updates and preliminary analysis conducted to test the revised methods. The detailed report is also included as part of the 2017 Coastal Master Plan documentation (Attachment C3-25 – Storm Surge and Risk Assessment).

This summary first describes the basic structure and functionality of the CLARA model and identifies how inputs from the storm surge and wave analysis are used for coastal flood risk estimation. Significant model improvements for the 2017 analysis are next described, including the goal, methods applied, and key lessons learned. A high-level visual summary of the revised risk analysis process is then presented and described. Finally, selected results from a preliminary investigation using the new model are described, focusing on a comparison to observed flood depth and damage data, sensitivity testing for parametric uncertainty, and an analysis to identify a suitable set of simulated storms to support the 2017 Coastal Master Plan analysis.

28.1 Summary of the CLARA Model

CLARA's structure is based on the principles of quantitative risk analysis, which describe risk as the product of the probability or likelihood of a given event occurring – in this case, the annual probability of storm surge flooding at different depths – and the *consequences* of that event – the damage that results from the flooding. In CLARA, references to flood risk are best understood as flood risk to structures, physical infrastructure, and other local economic assets.

CLARA uses several types of information to estimate flood depths and resulting damage. First are estimated peak storm surge and wave heights. Second are data that characterize the landscape, hurricane protection systems, and assets at risk along the Louisiana coastline. Along the coast, CLARA labels different areas as *unenclosed*, with no levees, floodwalls, or other barriers or with structures that do not fully enclose the population at risk; or *enclosed*, with hurricane protection that fully encloses the area in a ring and creates a "polder."

The structure of the CLARA model is illustrated in Figure 19. In the input preprocessing module, CLARA uses information about the study region and generates flood depth estimates in unenclosed areas and storm hazard conditions for a sample of hypothetical storms. It also records surge and wave conditions along protection structures. In the flood depth module, CLARA estimates flood depths for enclosed areas, with a particular focus on storm surge and wave overtopping and system fragility. CLARA also calculates equilibrium flood depths by distributing water among adjacent enclosed areas. The depth of the flood directly determines the amount of damage that occurs, so flood depths are inputs to the economic module. In this step, CLARA values the assets at risk from flooding and estimates the damage in dollars Fischbach et al. (2012).

Model outputs include summaries of flood depth and damage values at selected annual exceedance probabilities (AEP), which are statistical estimates of the flooding and damage expected to recur with a certain probability in each year. For example, the 1% or 100-year flood exceedance is the flood depth that has a 1% chance of occurring or being exceeded in each year. This is commonly referred to as the 1-in-100 or "100-year flood."

Expected annual damage (EAD) from storm surge flood events is another key model output. EAD is the average storm surge flood damage projected to occur in a single year, taking into account both the effective damage from a given type of storm and the overall likelihood of that storm occurring in a given year. The statistical methods used to estimate AEPs and EAD are based on the joint probability method with optimal sampling (JPM-OS), initially applied for surge risk estimation in coastal Louisiana after the 2005 hurricane season (Resio, 2007). These metrics are generated at each grid point in the model's spatial domain, but may be aggregated to larger spatial units (census tract, parish, etc.) as appropriate.

The basic structure of the CLARA model remains unchanged from 2012. However, substantial improvements have been made to the model since the original 2012 iteration, which is hereafter referred to as "CLARA v1.0." The new version developed for the 2017 Coastal Master Plan is described instead as "CLARA v2.0."

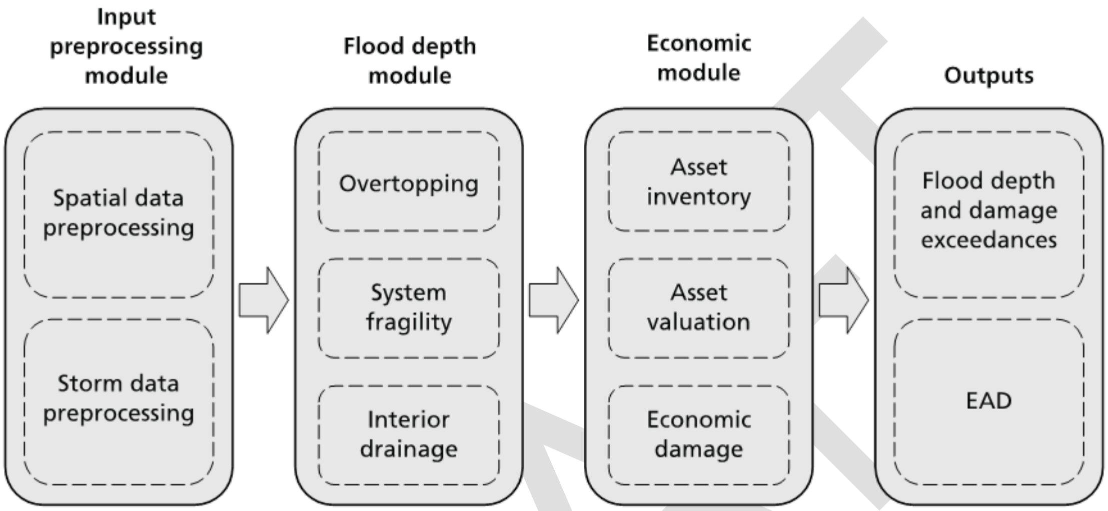

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Figure 19: CLARA model structure.

28.2 Model Improvements for 2017

Beginning in October 2013, RAND, CPRA, and The Water Institute worked in partnership to identify high-priority improvements for the CLARA model to implement in preparation for the 2017 Coastal Master Plan analysis. The high-priority needs related to coastal flood risk and damage analysis identified for this effort are summarized below.

28.2.1 Study Region Expanded to Account for a Growing Floodplain

The study region for the 2012 Coastal Master Plan effort was adopted from the 0.1% annual exceedance probability (AEP; or 1-in-1,000 annual chance) floodplain estimated by the U.S. Army Corps of Engineers (USACE) in its 2009 Louisiana Coastal Protection and Restoration (LACPR) report (USACE, 2009). Results from the ADCIRC storm surge analysis for the 2012 Coastal Master Plan, however, showed that the risk of flooding could extend further inland from coastal storms in some future conditions. Accordingly, a key step for 2017 was to expand CLARA's geographic boundaries northward to capture the growing floodplain, including towns such as Gueydan and Kaplan that were partially or completely excluded in the previous iteration.

To expand the study region, the Storm Surge and Wave Team used selected model results from the largest and most intense storm simulations from a set of 446 synthetic storms available for use in coastal Louisiana to identify a maximum plausible surge extent across the coast (assuming a “less optimistic” future landscape scenario 50 years into the future). These results were combined with 2010 U.S. Census urban area boundaries in GIS software to ensure urban areas were left undivided whenever possible, and a new boundary was subsequently identified. Results of this analysis are summarized in Figure 20 below. Portions of coastal Mississippi and Texas were also included (and are shown below) to allow the analysis to consider potential induced flood damage in these neighboring regions with proposed new projects in place.

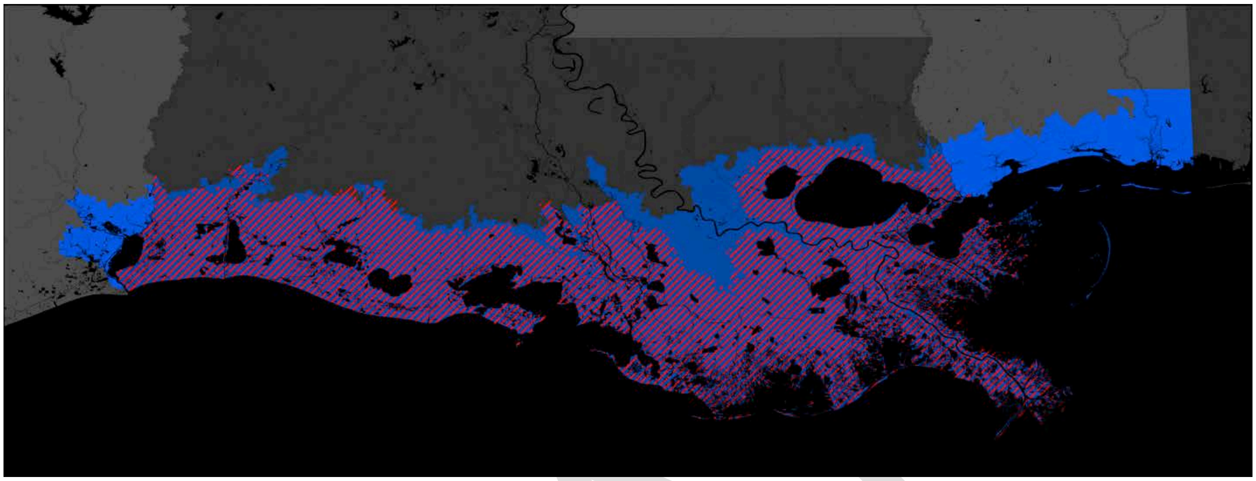


Figure 20: Geospatial domains: CLARA 1.0 (red) and new CLARA v2.0 (blue).

28.2.2 New Spatial Grid Developed to Support Higher Resolution Analysis for Coastal Communities

CLARA v1.0 was first applied to consider proposed risk reduction infrastructure investments, including protection structures such as levees, floodwalls, gates, and pumps, in addition to flood hazard mitigation projects such as elevating or floodproofing individual buildings. The latter project types, sometimes referred to as “nonstructural” risk reduction, were evaluated in a simplified, high-level way in the 2012 Coastal Master Plan analysis. These projects were defined using a handful of representative policy options, including structure elevations, floodproofing, or structure acquisitions. A simple set of decision rules was used to evaluate these project types uniformly in 56 different communities identified in the coastal region.

This high-level approach was useful for comparing the potential benefits of nonstructural investments with the benefits from structural risk reduction projects in a fair and consistent manner. However, after the 2012 analysis, CPRA determined that flood risk and benefits analysis at a higher level of spatial resolution would be helpful in refining nonstructural project strategies in support of the new Flood Risk and Resilience Program. It was also noted that a higher level of spatial resolution would improve flood depth and damage estimates and the subsequent mapping and communication of flood depth results.

To address this need, a new spatial unit of analysis for the flood depth and damage calculations was developed for CLARA v2.0. All aspects of the model were converted to this new grid, including the database of assets at risk. A preliminary analysis of nonstructural benefits and costs also was conducted using initial output at these grid points, with the goal of identifying specific areas with a substantial potential for risk reduction using building elevation, floodproofing, or structure acquisitions.

Spatial units in CLARA were redefined by first updating the economic units from 2000 to 2010 U.S. census blocks, which allows census data from 2010 and onwards to be used in the analysis. Then, a new set of grid points were created by combining the 2010 block centroids with a new grid of regularly-spaced points (RSPs) to ensure a minimum spatial resolution of 1 km x 1 km for the entire coast. The results of this exercise, which produced a total of 90,373 grid points for coastal Louisiana, are shown in Figure 21.

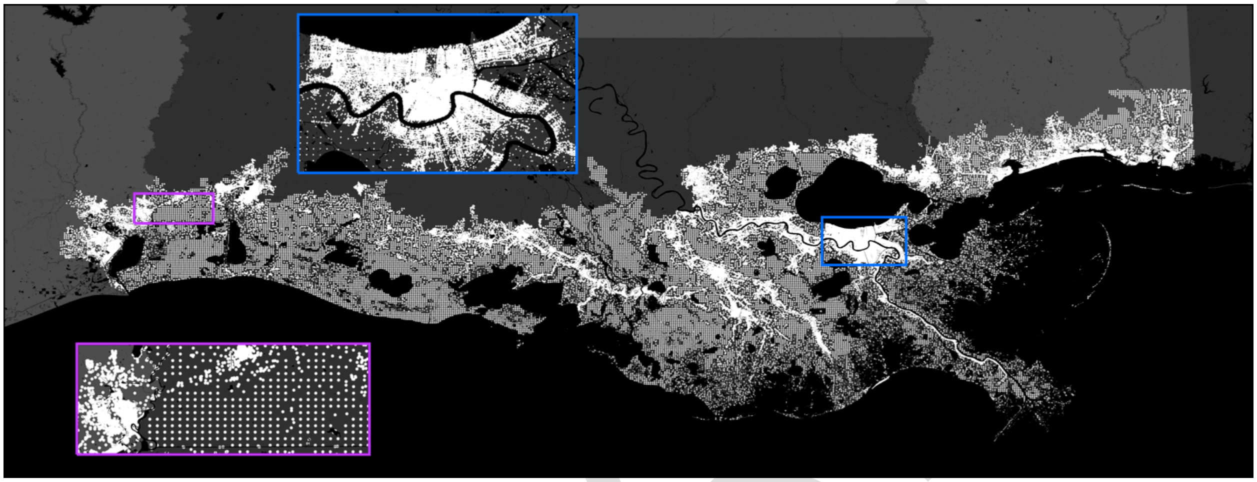


Figure 21: CLARA v2.0 final grid points.

28.2.3 Inventory of Coastal Assets At Risk Expanded and Improved

The inventory of assets at risk in CLARA v1.0 was based largely on data collected by USACE to support its planning in Louisiana subsequent to the devastating 2005 hurricane season. Much of the data describing the coastal population or assets at risk in the floodplain can be dated to the period immediately preceding Hurricanes Katrina and Rita, or is drawn from earlier iterations of the FEMA Hazards-US (Hazus) Multi-hazard model (FEMA, 2011) or the 2000 U.S. Census. In addition, the 2012 Coastal Master Plan analysis did not include data on some key classes of coastal assets, such as power plants, refineries, ports, or other types of critical infrastructure.

For 2017, the database of assets at risk was updated with additional and more recent data identified subsequent to 2012. These updates draw from parcel-level building inventories developed for recent studies and made available by USACE, as well as from a federal infrastructure dataset made available to the state to support its long-term disaster resilience planning.

Figure 22 summarizes the value of assets at risk across each major asset category in initial conditions, comparing the asset databases used by CLARA v1.0 and v2.0 for grid points in coastal Louisiana. Asset values at risk in CLARA are approximately 20-65% greater than in CLARA v1.0 due to the expanded study region, five years of additional growth in the baseline inventory, and improved inventory data that better captures the coast's recovery and redevelopment after the 2005 hurricane season.

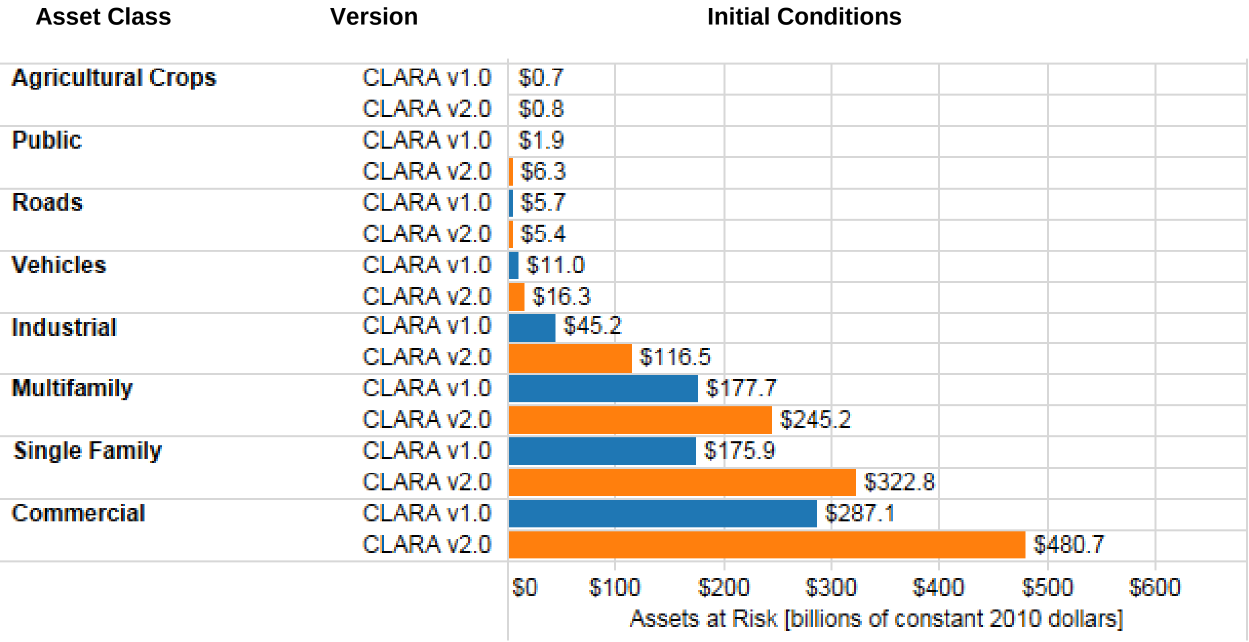


Figure 22: Assets at risk by asset class from CLARA v1.0 versus v2.0, initial conditions (2015).

28.2.4 Scenario Approach of Levee and Floodwall Fragility Improved Based on Recent Research

For the 2012 Coastal Master Plan analysis, CLARA v1.0 used a simplified model to estimate the probability that levees, floodwalls, and other protection structures might fail when faced with increasingly severe storm surge and waves. This approach was based on work done by USACE for the Interagency Performance Evaluation Taskforce (IPET) Risk and Reliability study (IPET, 2009). Since that time, additional studies have been completed on other protection systems or structures in the Louisiana coastal area, including Larose to Golden Meadow (USACE, 2013b), Morganza to the Gulf (MTTG) (USACE, 2013a), and the New Orleans Hurricane and Storm Damage Risk Reduction System (HSDRRS) armoring study (USACE Task Force Hope, 2013), all of which applied different assumptions and approaches to account for the additional risk introduced by potential structure failures. Based on this recent literature, CLARA's assumptions about protection system characteristics and the approach to estimating failure probabilities in CLARA v2.0 were revised, adding scenario uncertainty related to structure fragility to account for the continued lack of scientific consensus on this topic.

Specifically, a new set of fragility curves has been developed which predict the probability of breaches as a function of overtopping rates. A "Low" and "High" fragility curve has been added using assumptions from the MTTG study and the IPET study, respectively, for a total of four fragility curves which can be run. The IPET Low and High options vary in their assumptions about characteristic reach lengths: a shorter characteristic length subdivides levee reaches into a greater number of independent units, which leads to a greater chance of failure for each reach. The MTTG Low and High scenarios, alternately, use the same reach length but make different assumptions about how fragility curves are normalized for each characteristic reach length from the recent USACE estimates. A "No Fragility" overtopping-only case can also be run, as in prior versions.

28.2.5 Parametric Uncertainty Incorporated info Flood Depth Estimates

CLARA v1.0 was developed to address uncertainty from key external drivers looking out 50 years into the future, including sea level rise, coastal land subsidence rates, and future coastal economic growth, none of which could or can be reasonably assigned likelihoods. The 2012 approach used scenario analysis to capture the range of plausible outcomes from these drivers, but for any given scenario, the results calculated by CLARA v1.0 were deterministic (with the exception of a simulation of breaching due to failure of protection system features).

Given the number of steps, volume of input data, and overall complexity of the flood depth and damage calculations in CLARA, there are a variety of additional model uncertainties that were not captured in the scenario analysis, but that could be addressed through probabilistic uncertainty methods. Such methods could be used to estimate how parametric uncertainty propagates and expands throughout the modeling steps, which is especially significant for flood risk assessment because CLARA relies directly on outputs from other systems models.

For CLARA v2.0, a new approach was developed and implemented for quantifying parametric uncertainty – captured using estimates of model variance and reported using statistical confidence intervals – surrounding flood risk estimates. The new parametric uncertainty methods for CLARA v2.0 were designed to directly incorporate “upstream” estimates of uncertainty in the final flood depth estimates in addition to other sources of flood hazard and flood depth uncertainty. However, parametric uncertainty related specifically to asset exposure and structure damage calculations is not yet incorporated into CLARA v2.0. The parametric uncertainty approach is summarized in a subsequent section below along with selected test results.

28.3 Comparison with Hurricane Isaac

Much of the CLARA risk estimation approach cannot be separately calibrated or validated using observed historical data because the model produces statistical projections of flood depth and damage risk spanning a wide range of plausible events. However, some portions of the model, such as flood depth estimates from a single simulated storm, can be compared to past storm outcomes. Hurricane Isaac, which made landfall in Louisiana in August 2012, presented a unique opportunity to make such a comparison, as it affected protection systems around New Orleans and Plaquemines Parish that were nearly identical to how they are represented in CLARA’s current (initial) system condition (2015). This portion of the investigation therefore included a comparison between data gathered during and after Hurricane Isaac and CLARA’s economic asset database, response surface model, interior flood model, and damage calculations.

Hurricane Isaac made two separate landfalls on the Louisiana coast in late August 2012. Isaac was a storm with unique characteristics that present challenges for fitting it into CLARA’s JPM-OS statistical framework. On crossing 29.5 degrees north latitude, Isaac had a radius of maximum wind speed value of 30 nautical miles, a forward velocity of 4 knots, a central pressure of 973 mb, and a landfall angle of 41 degrees west of north. These values are on the extreme end or outside the range of parameters captured by synthetic storms in the currently available 446-storm JPM-OS suite. For instance, the majority of storms in the existing suite have a forward velocity of 11 knots, whereas the slowest storms move at 6 knots.

This analysis, described in detail in the full report, included the following comparisons:

1. The number of residential structures in Plaquemines Parish, by municipality, to the corresponding assets in the CLARA economic database;
2. Peak flood depths, surge elevations, and high-water marks experienced during Isaac in unenclosed areas, to the flood depths predicted by CLARA's response surface model for a synthetic storm with "Isaac-like" storm parameters (a synthetic storm with JPM-OS parameters set to those listed above);
3. Flood depths in enclosed areas from the "Isaac-like" synthetic storm to the flood depths experienced behind the Plaquemines and HSDRRS protection systems; and
4. A comparison of damage to residential assets from Hurricane Isaac to the damage produced by running the Isaac-like synthetic storm through CLARA.

The results of the comparison with Hurricane Isaac were ultimately of mixed utility. Ideally, a comparison to observed depths and damage from this event would build on a high-quality hindcast of the storm using ADCIRC and SWAN. But a reliable, accurate windfield model for the storm has not yet been produced and was not available for the analysis. As a result, high-resolution storm surge and wave simulations were not able to reproduce the storm's observed stillwater elevations and wave heights.

Instead, this comparison used an "Isaac-like" storm drawn from the JPM-OS framework rather than a direct reconstruction using ADCIRC as a next best alternative. This approach produced some insight but also had limitations, however, because currently available JPM-OS storms do not include a storm with Hurricane Isaac's unique characteristics and predicted depths did not match up with observed flooding in some locations.

A summary of the key findings and conclusions from the Isaac comparison exercises is given below. For more information, please see Attachment C3-25 – Storm Surge and Risk Assessment.

- Data quality in CLARA's inventory of economic assets is good: housing units in Plaquemines Parish, for example, are within 2% of reported values, and discrepancies between named communities in the parish are consistent with continuation of settlement trends observed in the last decade.
- Simulated surge elevations from synthetic storms based on the parameters of real, observed storms like Hurricane Isaac are of mixed quality and utility. Further, evaluation of synthetic storm performance in this regard is made difficult by the small number of monitoring stations for and their typical proximity to levee systems.
- Predicted overtopping and flooding in enclosed areas coincided with observed locations during Hurricane Isaac. CLARA calculated that levee failures were likely where none actually occurred, though this had little impact on modeled flood depths within the polders due to the volume of overtopping observed.
- Differences in economic damage assessments were primarily due to differences in the predicted extent of flooding.

28.4 Flood Depth Uncertainty

CLARA's estimates of flood depths incorporate both *aleatory uncertainty*, defined as the inherent and irreducible randomness of some systems or natural processes, and *epistemic uncertainty*, defined as uncertainty due to incomplete knowledge or data regarding the function or relationships in a given system. Uncertainty in CLARA is addressed through the use of three key approaches: (1) Monte Carlo simulation that impacts flooding on an individual-storm level, (2) resampling to generate confidence bounds around the exceedance curves summarizing the distribution of possible flood responses, and (3) scenarios designed to capture the variation due to deep uncertainty that impacts the flood response from all storms. Monte Carlo simulation is applied to estimate both aleatory and epistemic uncertainty at different points in the model. Resampling techniques and scenarios are used to characterize epistemic uncertainty. Table 15 summarizes sources of uncertainty in estimates of coastal flood depths that are addressed in CLARA v2.0.

Table 15: Sources of flood depth uncertainty addressed by CLARA.

Source of Uncertainty	Type of Uncertainty	CLARA Uncertainty Approach
Future state of the coastal landscape: sea level rise, subsidence, etc.	Deep	Scenario analysis
Future storm characteristics: changes to storm frequency, distribution of intensity, etc.	Deep	Scenario analysis
Variability in storm event characteristics	Aleatory	JPM-OS, parametric
Limited historical record of storms	Epistemic	Parametric, bootstrap sampling
Variability in surge and wave responses, given storm characteristics	Aleatory and Epistemic	JPM-OS, parametric
Limited observations of past surge and wave responses, given storm characteristics	Epistemic	Parametric
Impact of the chosen synthetic storm sample on exceedance estimates	Epistemic	*A posteriori* analysis
Impact of the chosen Monte Carlo and bootstrapping sample sizes on exceedance estimates	Epistemic	*A posteriori* analysis
Unknown geospatial correlations in surge and wave responses	Epistemic	Parametric, Monte Carlo simulation
Noise in ground elevation measurements	Epistemic	Parametric
Noise in input model (ADCIRC, UnSWAN) results	Aleatory	Parametric
Stochastic nature of levee and floodwall failure	Aleatory	Monte Carlo simulation
Incomplete understanding of levee and floodwall fragility	Epistemic	Scenario analysis
Variability in breach characteristics and failure consequences	Epistemic	Scenario analysis
Performance of pumping systems	Deep	Scenario analysis

Parametric uncertainties in individual storm results are incorporated into probability distributions representing the possible outcomes, while the model samples from the distributions of other parametric uncertainties to generate confidence bounds around the exceedance curves generated by all storms.

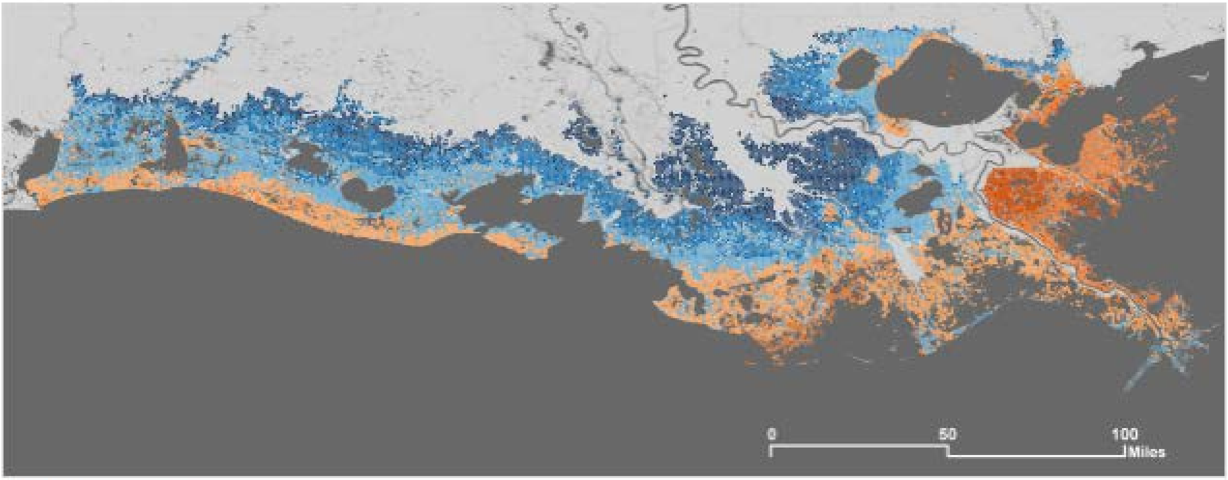
For example, the response surface fit on the ADCIRC and UnSWAN storm outputs is used to predict not only a mean surge and wave response for each synthetic storm, but also standard errors associated with the predictions. These standard errors are used to create multiple versions of each synthetic storm corresponding to different quantile values in the predicted distribution; a Markov chain Monte Carlo method is used to account for geospatial correlation in surge and wave behavior at nearby points along a protection system boundary.

Measurement error in digital elevation models stemming from noise in LiDAR datasets or uncertainty in predicted morphology is accounted for when converting calculated surge elevations and wave heights to flood depths. The brief record of observed historical storms has been leveraged through bootstrap sampling to produce uncertainty in the relative likelihood of synthetic storms with different characteristics, and this is reflected in the confidence bounds placed around estimates of flood depth exceedances. A detailed description of how these methods were incorporated can be found in Fischbach et al. (2015).

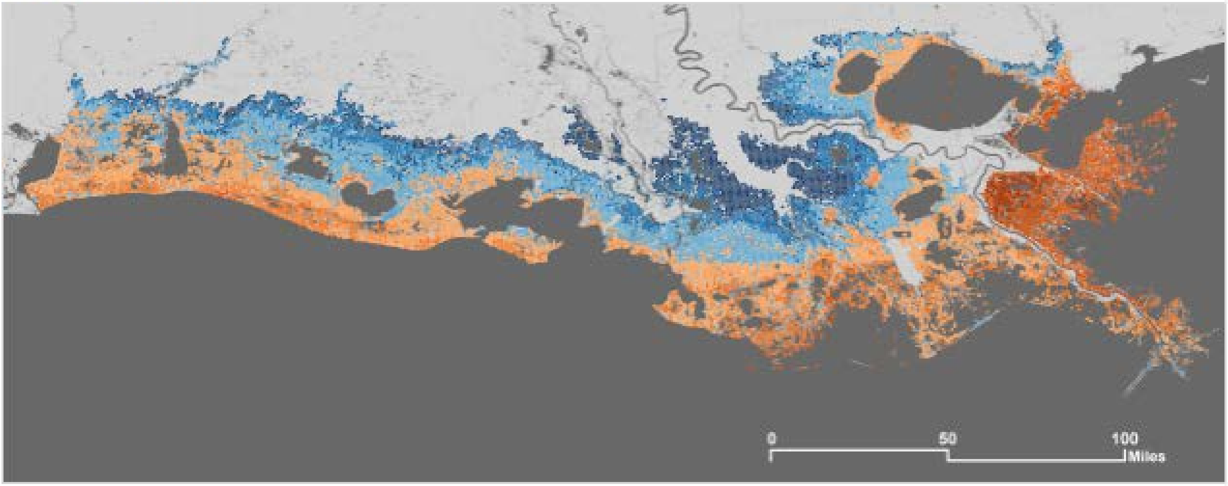
Selected results from the test-level analysis conducted to support CLARA model improvement and parametric uncertainty methods development are shown below. These results were created from a 446-storm set for initial conditions and in the Year 50 Less Optimistic future without action (FWOA) scenario, which was adopted for this purpose from the 2012 Coastal Master Plan analysis (CPRA, 2012b). Parametric uncertainty is represented with 10th, 50th, and 90th percentile results by interval. These results provide a snapshot of the testing results only, and are intended to give the reader a sense of the variation in results across the new parametric uncertainty calculations and CLARA v2.0's revised fragility scenarios.

Figure 23 shows a map of 1 percent AEP (100-year) flood depths in unenclosed areas of the coast 50 years into the future in one scenario. The figure shows how the 100-year depth results vary across CLARA's new 10th, 50th, and 90th percentile estimates, with each pane showing one percentile outcome.

10th Percentile



50th Percentile



90th Percentile

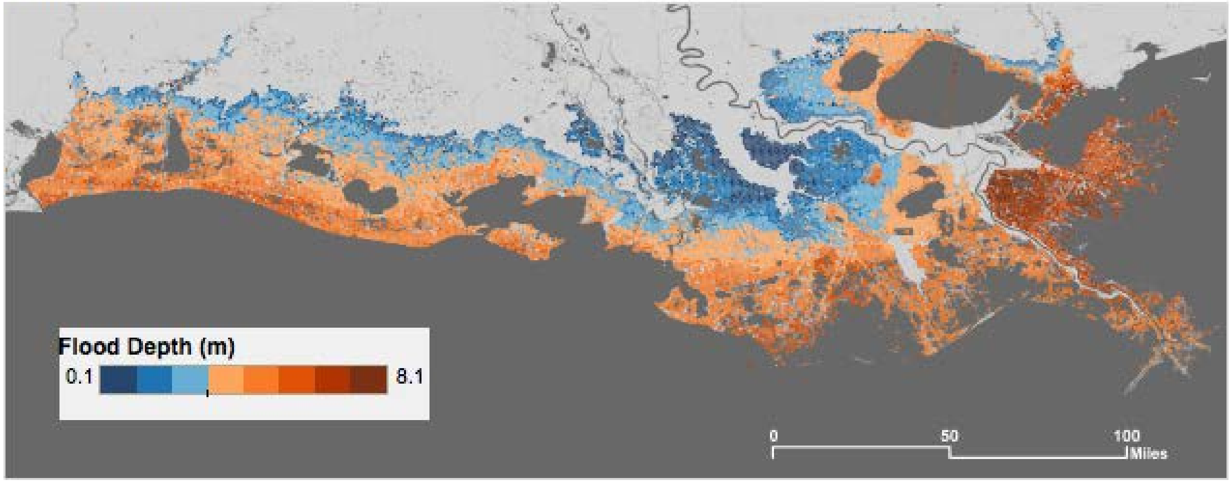


Figure 23: 100-year flood depths by grid point, year 50 less optimistic scenario.

Figure 24 shows damage estimates from CLARA v2.0, in terms of EAD. EAD is summarized in initial conditions (left pane) and in the Year 50 FWOA Less Optimistic scenario (right pane) in two different fragility scenarios, bracketing the most optimistic (IPET Low) and most pessimistic (MTTG High) approaches. The barplots are stacked to show the relative contribution from each asset class at the 50th percentile, with commercial, industrial, and single family residential assets contributing the majority of damage across cases. Vertical lines show the range of EAD results from the 10th to the 90th percentile across the parametric uncertainty range. Similar to the results observed during the 2012 analysis, this shows the dramatic increase in EAD that could occur over the next 50 years, as well as the range of outcomes observed across the new parametric uncertainty estimates.

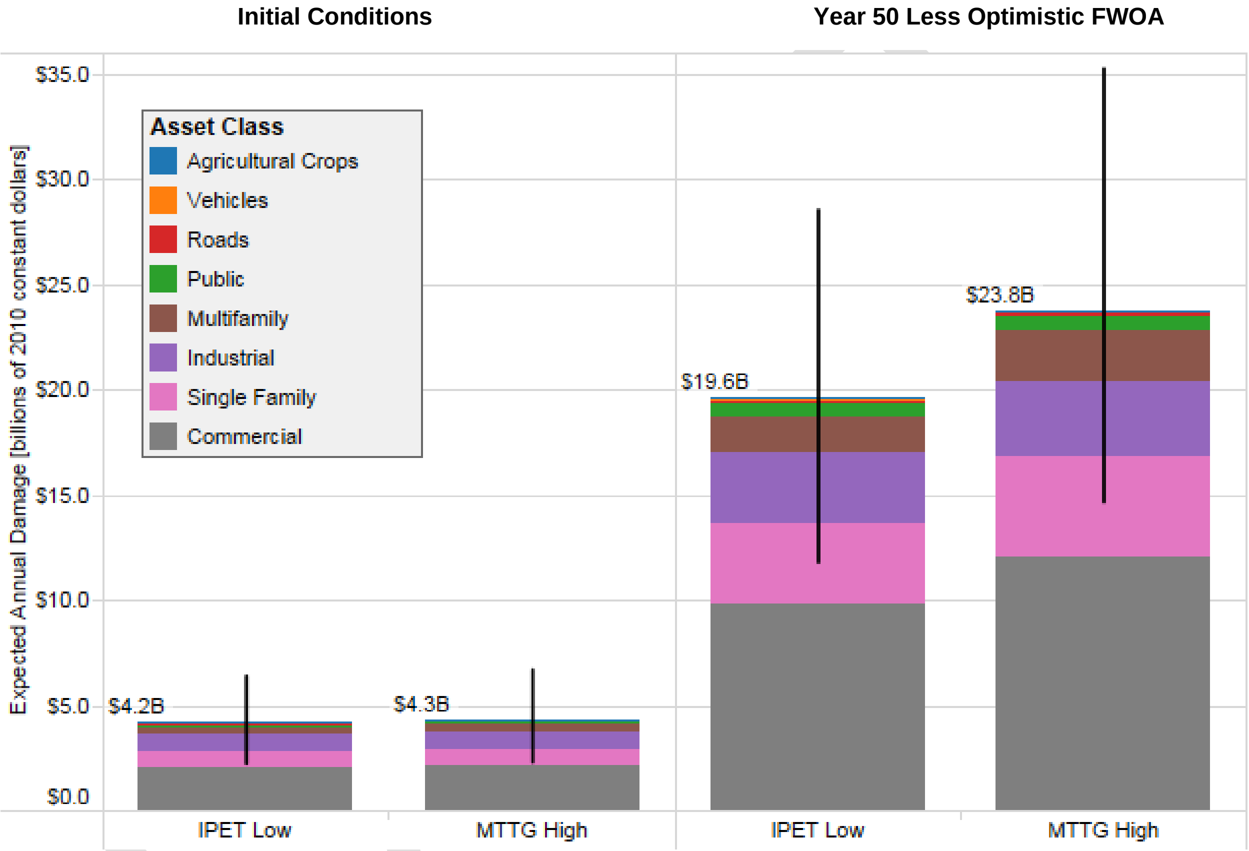


Figure 24: Coast wide EAD in two fragility scenarios, all percentiles, initial and less optimistic year 50 FWOA conditions (billions of 2010 constant dollars).

28.5 Storm Selection Analysis

A key goal to address using the revised CLARA v2.0 model and new parametric uncertainty approach was to better understand the potential tradeoffs CPRA should consider when using a smaller subset of tropical storms (referred to herein as storms) as a training sample for its statistical analysis of flood depths and damage. Fischbach et al. (2012) describe an initial evaluation of potential bias – comparing the subset of 40 storms chosen for the 2012 Coastal Master Plan analysis to a larger set of storms – but this evaluation still relied on a relatively small set to compare against (154 storms), and could not account for the additional uncertainty introduced when reducing the sample size.

To support the 2017 Coastal Master Plan analysis, a more thorough investigation was conducted to consider the tradeoffs associated with smaller subsets of storms. The first step was to conduct an initial screening by comparing a relatively large number of plausible subsets in selected geographic regions of the coast. Subsets were formed by eliminating storms from the full 446-storm set in ways intended to introduce minimal bias. For example, some subsets consist only of storms with a forward velocity of 11 knots, excluding storms from the 446-storm set with faster or slower progression. Other sets eliminate storms that follow “off-angle” tracks, or they may only include storms with minimum central pressures of 960 mb or lower.

Based on the preliminary screening and further input from CPRA, a limited number of storm subsets were then evaluated using the complete CLARA v2.0 depth and damage models for all areas of the coast. The performance of each storm subset was evaluated by estimating bias in predicted flood depths - comparing results from each subset against the outcomes from the full 446-storm reference set (Set 1 in Table 16). The estimated standard errors associated with these exceedance estimates were also compared. The storm subsets tested in this analysis, including number of storms and a description of key characteristics, are shown in Table 16 below.

Table 16: Characteristics of storm sets selected for investigation.

Set	Storms	Description
1	446	Reference storm set
2	40	2012 MP storm set: 10 storm tracks, 4 storms per track that vary c_p and r_{max}
3	60	2012 MP storm set expanded to 5 storms per track that vary c_p and r_{max}, plus storms with 975 mb c_p and central values for r_{max}
4	90	2012 MP storm set expanded to 9 storms per track that vary c_p and r_{max}
5	90	7 storms per track (excludes 1 930 mb and 1 900 mb storm) with 975mb storms using extremal (rather than central) r_{max} values
6	92	Set 3, with 960 mb and 975 mb storms on off-angle tracks only in E1-E4
7	92	Set 3, with 960 mb and 975 mb storms on off-angle tracks only in W3-W4, E1-E2
8	100	All central-angle, primary-track storms with 11-knot v_f, plus 975 mb storms with central r_{max}
9	110	All central-angle, primary-track storms with 11-knot v_f, plus 975 mb storms with extremal r_{max}
10	120	All central-angle, primary track storms with 11-knot v_f, including 975 mb storms
11	154	Set 4, plus all 960 mb and 975 mb storms on primary, off-angle storm tracks

Figure 25 summarizes the average coast wide 100-year flood depth bias (in terms of root mean squared error or RMSE, y-axis) and coefficient of variation (point size) for each set, plotted against number of storms (x-axis). Colors indicate whether the set includes 975 mb storms, and shape indicates whether off-angle tracks are included. Bias is estimated relative to the flood depth results from Set 1, the reference set.

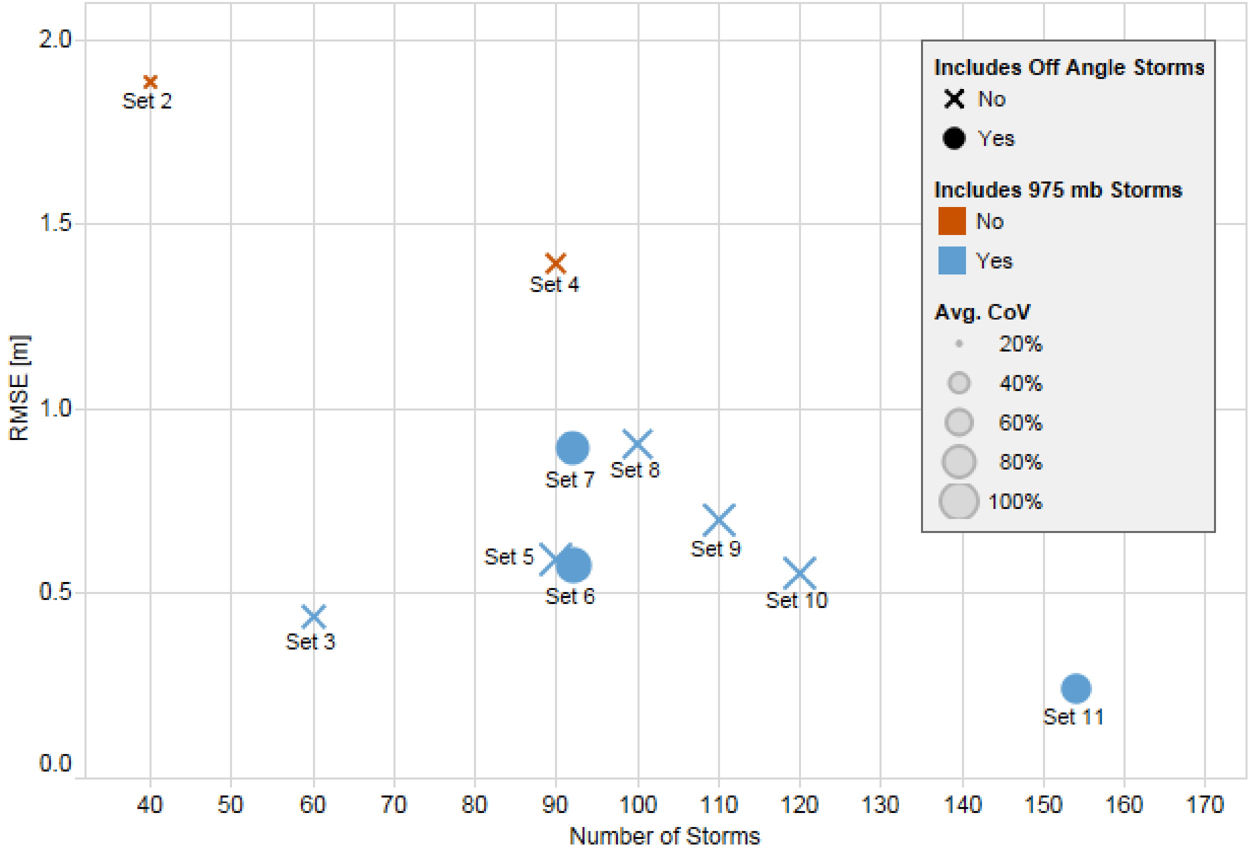


Figure 25: Average coast wide bias and variation by number of storms, 100-year flood depths.

Summary results show that average flood depth bias by point at the 100-year interval varies from less than 0.25 m to nearly 2.0 m, depending on the storm sample. The flood depth results show a tradeoff between the number of storms and the resulting bias when compared with the reference set of 446 storms. Results show that nearly all storm sets tested produce lower bias when compared with the 2012 Coastal Master Plan 40-storm set (Set 2). Substantial improvement is noted when storms with 975 mb central pressure were included, as well as with the addition of off-angle storms in some cases.

Figure 26 shows a coast wide comparison of the storm sets in terms of damage (EAD) bias. The y-axis indicates the bias in coast wide EAD relative to the full 446-storm set (Set 1); the three points for each subset, from bottom to top, represent the bias associated with the 10th, 50th, and 90th percentile values, respectively, of EAD.

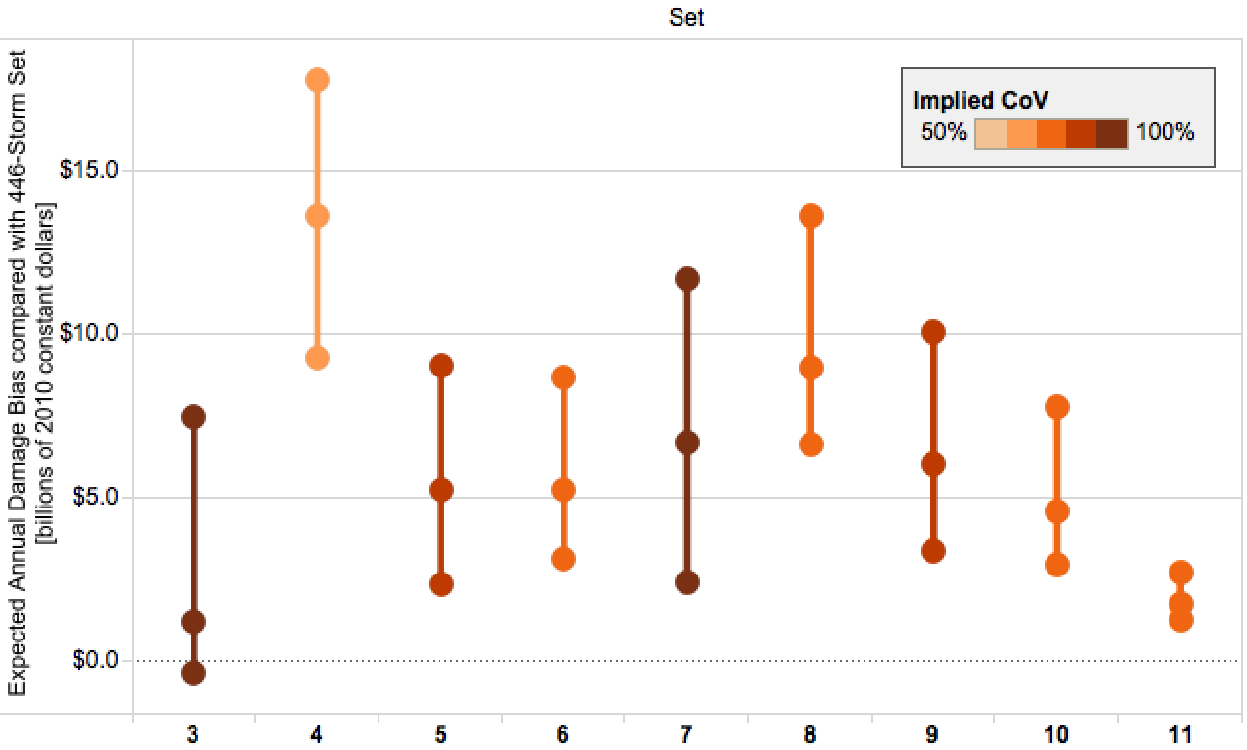


Figure 26: Coast wide bias in terms of expected annual damage (billions of 2010 dollars).

When considering damage bias, results show that Set 11 yields a much smaller variation in bias over the experimental design tested, compared to the other subsets. Considering only sets with fewer than 100 storms, Set 3 is the best performer at the median, but it includes a wider range of results across the parametric distribution and it has performance comparable to Sets 5, 6, and 10 when comparing the 90th percentile results.

Of the subsets tested, Set 11 (154 storms) appears to yield the best balance of results. This set shows relatively low bias compared with the reference set in terms of both flood depth and damage, no concerning spatial patterns of bias, and reasonable performance in enclosed areas (particularly Greater New Orleans; see supporting appendix). This storm set will be used to evaluate and compare coast wide alternatives in the 2017 Coastal Master Plan analysis.

In addition, Set 3 produces the best results among the smaller sets. Given the much smaller number of storms required and relatively unbiased performance at the median, Set 3 will be used to support the comparison of individual structural risk reduction projects during 2017 model production.

29.0 Data Management

29.1 Introduction

As with any effort of this scale, a comprehensive, structured data management plan is crucial to maximize the utility and organization of the various data resources. During model execution and output evaluation, data files must be compatible/standardized, easily accessible and transferable across modeling team members. Short- and long-term storage targeting user accessibility of these data sets is also of particular importance along with archival procedures to maintain the data record.

29.2 File Naming Convention

Large, multi-member, data generating and sharing efforts, such as the 2017 Coastal Master Plan modeling effort, benefit from proactive development of a file naming convention, especially when the primary data storage vector is file based. Building upon the 2012 Coastal Master Plan modeling effort, the file naming convention for the 2017 Coastal Master Plan modeling effort includes some requirements to ensure consistency and ease of programming interactions. These requirements include restriction against any use of spaces, use of underscores to delimit components, use of hyphens to delimit elements within a component, only capital letters, and padding all components with leading zeros if a numeric component and trailing capital Xs if an alphabetic component exists. The file naming convention has 13 filename components: 12 underscore delimited to the left of the period and one to the right. Specifically, the components of the file naming convention include: Master Plan year, Scenario, Grouping, CLARA scenario, Uncertainty, Variance, Region, File type, Start-End year, Subroutine, and Parameter (e.g., MP2017_S01_ G001_ C001_U01_ V01_PBB_I_01-05_H_NH4XX.OUT).

29.3 Online Code Repository

A source code versioning system is critical to the success of any large-scale programming effort. A code repository serves not only as a central, authoritative source of the latest source code version, but also as a history report, a milestone tracker, and a collaborative tool for geographically dispersed programming teams. For the 2017 Coastal Master Plan modeling effort, a Subversion (SVN) repository was established to host all Integrated Compartment Model (ICM) source code. An account registration and management system was coupled with the CPRA Coastal Information Management System (CIMS) to control read/write access to the code. Contributing users are recommended to interact with the repository by using the TortoiseSVN[7] (http://tortoisesvn.net) client for Windows or the SVN command-line client for Linux. Users with read-only access may browse the repository either through the web interface or a visual SVN tool, such as the TortoiseSVN repository browser.

29.4 In-Code Documentation

Source code documentation explains how unique parts of the application work. Doxygen1 (http://doxygen.org) has been adopted for all in-code documentation in the 2017 Coastal Master Plan ICM source code, with HTML as the output format. Doxygen is a tool that converts in-code comments into compiled reports in several formats. By using the HTML report format, which can be viewed in any modern web browser, programmers can tag their code using the <...> format, where "…" are HTML-specific tags. In order to prevent the HTML pages from becoming out-of-date, a nightly build tool was created to automatically retrieve the most recent version of the code from SVN, run the Doxygen tool, and publish the newly-created HTML pages on the Master Plan Data Server website.

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[7] Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

29.5 MPData Server Sandbox

The Master Plan Data Server (MPData Server) Sandbox is comprised of large back-end file storage hardware with an attached password-protected web front-end interface. The MPData Server serves as a central repository for task and subtask related documents for each master plan team for the 2017 Coastal Master Plan development effort. Differential user access was assigned based on user roles allowing team members the ability to selectively share project information. Following model development and execution, the final 2017 Coastal Master Plan data files will be accessible through the MPData Server public interface. Although not present prior to 2014, the MPData server also houses the final versions of the 2012 Coastal Master Plan outputs.

29.6 Production Data Sharing with Secure File Transfer Server (sFTP)

The master plan models are expected to generate at least 200 terabytes of data across hundreds of scenario and project runs. Since model deployment is iterative (i.e., subsequent models require other model results as inputs), a large server resource is needed. The geographically dispersed nature of the modeling teams (e.g., Lafayette, Baton Rouge, New Orleans) and the semi-automated nature of the model runs require an internet accessible resource supporting a secure protocol in which models can programmatically push and pull data as needed. This need was addressed with a large sFTP server attached to a redundant array of independent disks (RAID) ensuring high performance and data protection with the array. This resource will be utilized during production runs and through the quality control process until decisions are made as to which runs will be kept long term. Those runs will ultimately be kept on the MPData Server Sandbox.

29.7 Data QA/QC Process

Some degree of error is a reality for any data intensive effort. A quality assurance and control (QA/QC) process helps ensure confidence in the final data product. The integrated compartment and Ecopath with Ecosim (EwE) modeling outputs are all subjected to various levels of review to confirm accurate execution of the logic and algorithms of the models. Numerous checks will be performed on modeled variables which will vary across the models but may include: bar and time series charts which allow quick review of summary statistics such as minimum/maximum/mean, overview or cross section maps, and tables of strategically developed summary values. Of the hundreds of model runs, a subset of output will be directed to reviewers for QA/QC. Details of the review will be logged and kept for the permanent record.

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Chapter 4: Modeling Outputs and Results

Chapter is forthcoming

Chapter 5: Use of Model Outputs and Conclusions

Chapter is forthcoming